MAX '91

Flare Research at the Next Solar Maximum

(NASA-TM-89700) MAX '91: FLARE RESEARCH AT THE NEXT SOLAR MAXIMUM (NASA) 42 pCSCL 03B

N88-14919

Unclas
G3/92 0117255

7

January 1988

MAX '91

FLARE RESEARCH

AT THE

NEXT

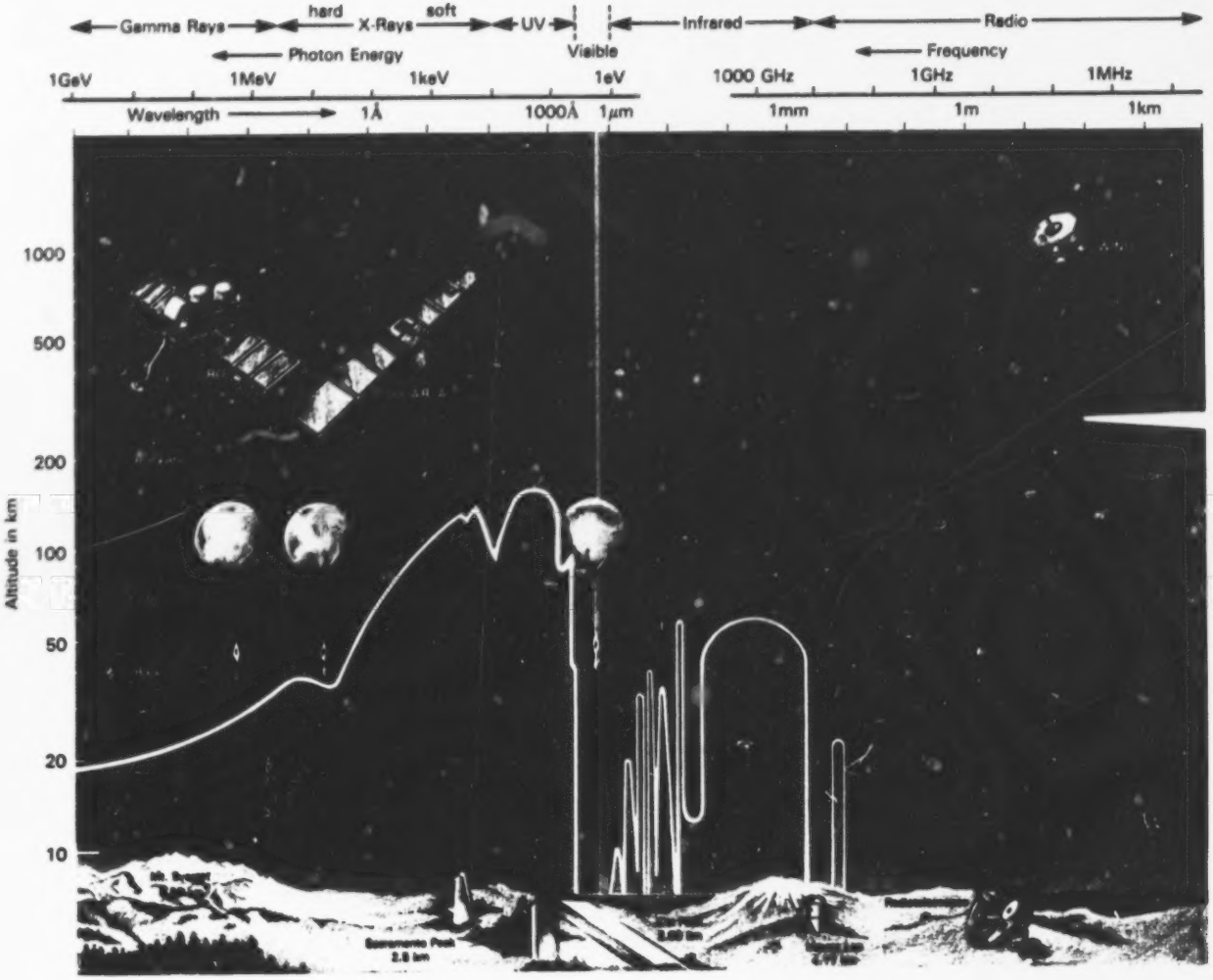
SOLAR MAXIMUM

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

PAGE 11 INTENTIONALLY BLANK

PRECEDING PAGE BLANK NOT FILMED

ORIGINAL PAGE
COLOR PHOTOGRAPH



ORIGINAL PAGE
COLOR PHOTOGRAPH

Frontispiece

Cross section through the Earth's atmosphere showing the altitude and the approximate wavelength coverage of the different spacecraft, rockets, balloons, and ground-based observatories that make up the Max '91 observing program. The solid white line shows the altitude as a function of wavelength where the intensity of the solar radiation is reduced to half its original value.

PREFACE

This document grew out of a meeting of interested scientists held at the California Institute of Technology in Pasadena on Friday, January 9, 1987. At that meeting many presentations were made of plans and aspirations for making observations of solar flares at the next solar maximum. It was realized that the scientific benefit of these observations would be greatly increased if they were coordinated together in a manner similar to the highly successful approach used during the previous solar cycle. Consequently, a group of volunteers agreed to write a report which would be the first step in developing such a coordinated plan. This report is the result of their efforts over the last six months. It was prepared by the following people:

Brian Dennis,	co-chairperson	Goddard Space Flight Center
Richard Canfield,	co-chairperson	University of Hawaii
Marilyn Bruner		Lockheed Palo Alto Research Lab.
Gordon Emslie		University of Alabama, Huntsville
Ernest Hildner		Space Environment Lab., NOAA
Hugh Hudson		University of California, San Diego
Gordon Hurford		California Institute of Technology
Robert Lin		University of California, Berkeley
Robert Novick		Columbia University
Ted Tarbell		Lockheed Palo Alto Research Lab.

Valuable comments and suggestions based on early drafts were also made by David Bohlin, Harjit Ahluwalia, Dennis Peacock, Donat Wentzel, Keith Strong, Stuart Jordan, Daniel Spicer, and the members of the NASA Solar and Heliospheric Physics Management and Operations Working Group, who reviewed a preliminary version in March, 1987.

The co-chairpersons carried out the final editing, and they take full responsibility for any errors or omissions.

PRECEDING PAGE BLANK NOT FILMED

PAGE IV INTENTIONALLY BLANK

TABLE OF CONTENTS

PREFACE v

INTRODUCTION AND SUMMARY 1
- Long-Duration Balloon Flights 1
- Ground-Based Instrumentation 3
- Coordination of Observations 4
- The International Flares 22 Program 4

THE MAJOR SCIENTIFIC ISSUES 5
- Energy Buildup and Flare Onset 5
- Energy Release and Transport Mechanisms 5
- Theory and Modeling 7
- Atomic, Nuclear, and Plasma Physics 7
- Solar Terrestrial Effects 7

REQUIRED OBSERVATIONS 8

- Balloon Observations 8
  - High-Spatial-Resolution Hard X-Ray and Gamma-Ray Imaging Spectroscopy 8
  - High-Spectral-Resolution X-Ray and Gamma-Ray Spectroscopy 9
  - Sensitive High-Energy X-Ray Polarimetry 9
  - High-Resolution Optical Imaging and Polarimetry 12
  - Long-Duration Balloon Capabilities 12

- Ground-Based Observations 13
  - Dedicated vs. Nondedicated Facilities 13
  - Optical Magnetic Field Observations 13
  - Optical Vector Magnetic Field Observations 13
  - Optical Imaging Spectroscopy 14
  - Microwave Imaging Spectroscopy 14
  - Dekametric, Metric, and Decimetric Observations 16
  - Synoptic Observations and Analysis Facilities 16

- Other Observations 16

COORDINATION OF OBSERVATIONS AND ANALYSES 18
- International Programs 18

PROGRAM PLAN 20
- Phase I: Planning and Instrument Development 20
- Phase II: Coordinated Observations and Specialized Campaign 20
- Phase III: Analysis and Interpretation 20

CONCEPTUAL BUDGETS 22
- NASA Augmentation Budget 22
- NSF Augmentation Budget 23

PRECEDING PAGE BLANK NOT FILMED

PAGE vi INTENTIONALLY BLANK

TABLE OF CONTENTS (continued)

APPENDICES

APPENDIX A. SPACE-BASED OBSERVATIONS 25
Solar-A 25
Gamma Ray Observatory (GRO) 25
Global Geospace Science (GGS) 26
Ulysses 26
GOES 26

APPENDIX B. OTHER POSSIBLE SPACE OBSERVATIONS 27
The Solar Maximum Mission (SMM) 27
Satelite de Aplicaciones Cientificas (SAC-1) 27
SAMEX 27
Shuttle/Spacelab/Space Station 27
Spartans 27

APPENDIX C. POSSIBLE BALLOON-BORNE INSTRUMENTATION 29
Gamma-Ray Imaging Device — GRID 29
High-Resolution Gamma-Ray and Neutron Spectrometer — HIGRANS 29
High Energy X-Ray Polarimeter — HXP 30
Solar Optical Universal Polarimeter — SOUP 31

APPENDIX D. CURRENT LONG-DURATION BALLOON FLIGHT CAPABILITIES 33
Improvements to LDBF Capabilities 34

INTRODUCTION AND SUMMARY

The ability to generate magnetic fields, to release their energy impulsively, and to accelerate particles to high energies is a common characteristic of cosmic plasmas at many sites throughout the universe, from magnetospheres to active galaxies. These processes play a central role in the overall physics of the system at each site where they are observed. The physical understanding of these processes — both what they are and why they occur — is one of the primary goals of astrophysics and solar-terrestrial physics. Nowhere can one pursue the study of this basic physics better in a naturally occurring astrophysical setting than in the active Sun, where solar flares and their terrestrial effects are the direct result of magnetic energy storage, its impulsive release, and high-energy particle acceleration.

Among the many discoveries of the Solar Maximum Mission were the 154-day periodicity of large flares, the prompt acceleration of heavy ions to gamma-ray energies, extremely fast (tens of milliseconds) fluctuations of X-rays produced by nonthermal electrons, and the explosive flows of X-ray plasmas during the impulsive phase. Recent advances in both space and ground-based instrumentation, made since the previous solar maximum, allow us now to make much more powerful observations. Because of the much better spectral and spatial resolutions and the higher sensitivity of the new instruments, it is now possible, for the first time, to observe some of the most fundamental processes involved in solar flares on their intrinsic spatial, spectral, and temporal scales. The next solar maximum, the period of high solar activity between 1990 and 1994, provides a rare opportunity to exploit these new capabilities through observations of high-energy flare phenomena and the magnetic and thermal context in which they occur. It is the purpose of this document to describe a comprehensive Max '91 program of such observations for the next solar maximum. We indicate how these observations might be made in a timely fashion and outline how they could be coordinated to obtain the maximum return within the limited resources that are available to us.

The diagnostic power of this new instrumentation is qualitatively different from what was available during the previous solar cycle. It allows us to go deeper than the question of what a flare is; it allows us to gather spectra and images that are relevant to the question of what causes a flare to happen in the first place. We can now seriously address not only the impulsive energy release with its attendant heating and particle acceleration, but also the magnetic and thermodynamic environment that leads up to it. We can now, for the first time, seriously aspire to understand several of the most fundamental questions of solar flare physics:

- How and where is flare energy stored?
- What causes flare energy release?
- What are the mechanisms of flare energy release?
- How are particles accelerated?
- What are the mechanisms of flare energy transport?
- How do flare effects propagate to the Earth?

To compellingly address these central scientific questions, coordinated observations of electromagnetic radiation and energetic particles must be made from spacecraft, balloons, rockets, and ground-based observatories.

As shown in Figure 1, the Max '91 observing program will cover the full spectral range of flare emissions and will provide new insight into the three fundamental aspects of solar flares:

- Buildup, storage, and dissipation of magnetic energy.
- Acceleration of charged particles.
- Plasma heating and mass motions.

Flare observations during the next maximum will also provide information of importance in the areas of flare prediction, chromospheric and coronal abundances, and the relationship between solar flares and their astrophysical analogues. Continuing theoretical work and flare modelling involving plasma physics, magnetohydrodynamics, kinetic theory, particle and radiation transport, and atomic and nuclear physics, will provide the intellectual framework on which the observations can be interpreted.

The core space missions for the Max '91 program will be the Japanese Solar-A spacecraft, the Gamma-Ray Observatory (GRO), and the WIND spacecraft of the Global Geospace Science (GGS) program. Because of their expected long lifetimes and the continuous nature of their observations, these space missions play a leading role in defining the programmatic approach for the next solar maximum.

Many of the required observations will be made from high-altitude balloons and from the ground. The enhanced capabilities of advanced instrumentation on long-duration balloon flights and at ground-based observatories will provide unique observations that address the scientific objectives in ways that the spacecraft will not achieve. ***We therefore recommend the timely initiation of a broad-based observational program at the next solar maximum, to include the following elements:***

Long-Duration Balloon Flights

The new capability of making long-duration balloon flights lasting as long as 15 to 20 days provides the opportunity to make unique observations of hard X-rays, gamma-rays, and optical emissions. As shown in the frontispiece, these flare emissions penetrate the Earth's atmosphere to at least the ~130,000-ft (40-km) altitude of these balloons. These emissions could be measured for several large flares and many smaller flares on each balloon flight, and powerful new

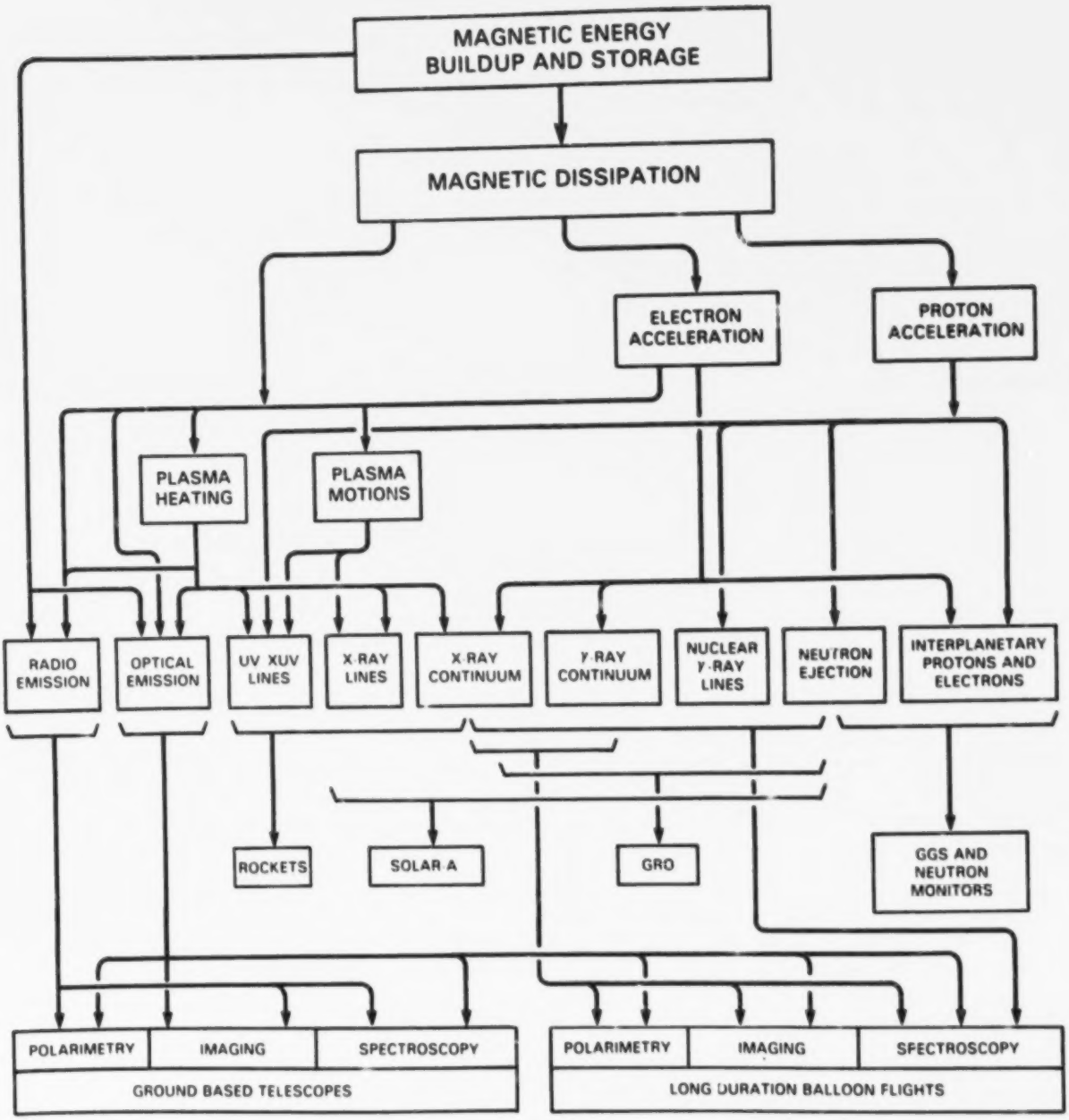


Figure 1. Schematic block diagram showing the major components of a solar flare, their observables in terms of photons across the electromagnetic spectrum and interplanetary particles, and the different components of Max '91, the planned observing program for the next solar maximum. Note that Solar-A, GRO, and GGS are three space missions discussed in Section 3 that will provide valuable observations during Max '91.

instruments could be flown with capabilities now found on any spacecraft expected to be in space during the next maximum. ***To take advantage of the advanced diagnostic potential of long-duration balloon observations and their relatively low cost compared to space observations, we strongly recommend a major enhancement to NASA's commitment to scientific ballooning at the next maximum.***

The following advanced instruments could readily be built at modest cost and flown on balloons in time for the next maximum:

- A hard X-ray and gamma-ray imager with arcsecond angular resolution could, for the first time, fully resolve flaring magnetic loops and trace the variation of the electron spectrum along the loops.
- A hard X-ray and gamma-ray spectrometer with keV energy resolution could, for the first time, resolve gamma-ray lines and determine their widths and shapes, and also clearly separate the thermal and nonthermal components of the hard X-ray continuum spectrum.
- A hard X-ray polarimeter could, for the first time, establish the degree of beaming of accelerated electrons through the determination of the polarization at the few percent level up to energies as high as 100 keV.
- An optical spectrometer/polarimeter with far better spatial resolution and stability than is possible from the ground could, for the first time, quantitatively measure the energy content of active regions before, during, and after flares through the measurement of vector magnetic and velocity fields.

In order not to postpone these opportunities to do forefront science for at least a decade (until the next solar maximum in the year 2002), ***it is essential that instruments in each of these categories be selected and funded as soon as possible so that they can be ready for their first flights no later than 1991.***

Long-duration balloon flights with heavy payloads have been pioneered by solar physics and cosmic ray groups with three successful flights conducted to date from Australia. However, it is important for the success of the Max '91 program that alternate launch sites and flight paths be investigated, particularly in the northern hemisphere, to allow each of the instruments at least two flights per year. While the present balloon capabilities are adequate for many solar observations, it is clear from the first flights that the reliability must be improved and the capabilities expanded, particularly in the areas of auto-ballasting, command, telemetry, navigation, and power.

Ground-Based Instrumentation

Ground-based optical and radio observations during the next solar maximum can provide, at relatively low cost, unique diagnostic information on the magnetic and thermal environment of flare energy release that will not be obtained from spacecraft or from balloons. Optical observations are required to locate and measure magnetic energy buildup, through vector magnetic field measurements of the morphology, evolution and nonpotential character of magnetic structures in the photosphere and chromosphere. Radio observations are required to make field strength measurements directly at coronal levels, as close as possible to the likely initial energy release and particle acceleration sites. Both optical and radio observations are required to determine the preflare and flare thermodynamic environment of particle acceleration.

The duration, unpredictability, and simultaneous broad spectral range of solar activity demand **dedicated** ground-based facilities for its study. However, facilities at dedicated ground-based solar observatories are presently so inadequate that unless additional instruments are built, the required observations will have to be made using poorly suited national facilities. If this happens, past experience shows that successful coordinated observations will be made of only a handful of flares over the entire next solar cycle. ***In order to redress this inadequacy of existing ground-based instrumentation for dedicated solar activity studies, we strongly recommend a major commitment to dedicated ground-based instrumentation at the next maximum.***

Taking advantage of recent technological developments, optical instruments can now be built or upgraded to make them much more powerful than those presently in existence. The most important optical instruments are—

- A second dedicated vector magnetograph at a site far from the only existing one (at Marshall Space Flight Center), to provide the maximum practical observational database and two independent measurements as a cross-check, for both predicting solar flares and understanding how their energy is stored.
- A second dedicated high-speed longitudinal magnetograph at a site far from the existing one (at Big Bear Solar Observatory), to provide the maximum practical observational database and two independent measurements as a cross-check, for determining the role of emerging, submerging and advecting magnetic flux in flare energy release.
- A dedicated digital imaging spectrograph modeled after the Multiple Diode Array and echelle spectrograph at the National Solar Observatory (Sacramento Peak) to provide the maximum practical observational database on the characteristics of energetic particles and flare heating in the chromosphere.

The most important new radio capabilities are—

- Dedicated combined imaging and spectroscopy, to measure magnetic fields in the vicinity of the energy release site and to determine the characteristics of energetic electrons in the corona.
- Improved scheduling, operational flexibility, calibration, time resolution, and spectral coverage of the Very Large Array (VLA), to more effectively exploit the high spatial resolution of this powerful facility.

During the last decade, there have been many improvements in panoramic solid-state detectors, minicompuers, and high-speed digital recording and analysis devices, accompanied by a significant drop in their costs. These developments enable major improvements (about two orders of magnitude) to be made in the combined spatial, spectral, and temporal resolution compared to the last solar maximum. Because flares vary so dramatically in space, time, and spectral characteristics, it is important to utilize these technological developments for Max '91 in order to take advantage of this greatly improved diagnostic power.

Coordination of Observations

It is essential that the flare observations across the electromagnetic spectrum, together with neutron and charged-particle measurements, be tightly coordinated to obtain the greatest scientific return. It is also necessary to predict the most probable types and sites of solar activity, to appropriately tailor the observational parameters of ground and space-based instruments, and to communicate the operational information to all observers. To provide these coordination and prediction services, ***we recommend that a dedicated full-time scientific coordinator be located at an institution with advanced prediction and image communication capabilities.***

The International Flares 22 Program

The world-wide distribution of ground and space-based facilities, and the multinational character of the core scientific community, compel scientific planning, data exchange, and scientific meetings on a global scale. ***We recommend an international program of solar flare research during Cycle 22, to be called Flares 22. The four-year period of observations should start in 1991 and be followed by a three-year program of data analysis and interpretation.***

Within a realizable program of modest budget, major progress toward the Max '91 scientific goals can be achieved with the coordinated program of observations outlined in this report. Combining the planned space programs with long-duration balloon flights and ground-based observations will ensure that many results will be obtained that will be of major significance to solar physics and indeed to all of astrophysics. Success in this endeavor requires that an early start be made on building the instrumentation, enhancing the long-duration balloon capability, and developing and proving the national and international mechanisms for coordinating observations and campaigns.

THE MAJOR SCIENTIFIC ISSUES

After more than a century of recorded observations, the solar flare remains very much an enigma. It is generally accepted though it has never been quantitatively measured, that the approximately 10^{32} ergs required for a major solar flare is stored in stressed magnetic field structures. However, the means by which this energy is suddenly released (on timescales of a few minutes or, in some cases, seconds), and subsequently transported throughout the solar atmosphere is far from fully understood.

Solar flares produce enhanced emissions across the entire electromagnetic spectrum, from kilometric radio emission through microwave, optical, ultraviolet, and soft X-rays, to hard X-rays and gamma rays. A thorough understanding of the physical processes which lead to each of these signatures, and the interrelationships among them, is essential to answering the fundamental physical questions of energy storage, release, and transport in solar flares. It has been established from hard X-ray and gamma-ray observations made during the last solar maximum that the primary energy release in solar flares involves the acceleration of a considerable number of particles, both electrons and protons. Such high-energy processes play a role not only in solar flares, but also in a wide variety of other astrophysical sites, such as planetary magnetospheres, stellar flares, supernovae, and active galactic nuclei. The proximity of the Sun affords us a unique opportunity to investigate these fundamental astrophysical processes at a level of detail not possible elsewhere.

Energy Buildup and Flare Onset

The first of the major scientific questions identified in the Introduction concerns the preflare storage of energy. This is generally agreed to occur in the form of currents, which are reflected in nonpotential magnetic fields in the photosphere and corona, but direct evidence of any build-up of magnetic energy prior to a flare has been difficult to obtain. As shown in Figure 2, ground-based magnetographs can be used to infer photospheric vector magnetic fields. While such vector magnetograms have shown significant deviations from a current-free configuration before a flare occurs, there is a clear need for two further improvements.

First, better spatial resolution is required in order to directly measure the amount of magnetic energy released in solar flares. The present measurement uncertainty of active region energy content is about 10^{32} ergs, which is about the amount of energy released in a large flare, and this uncertainty decreases linearly with increasing spatial resolution.

Second, there is a clear need to directly measure the coronal magnetic field through observations of gyrosynchroton and gyroresonance radio emission. In addition, we must also continue the development of techniques for interpreting the measured line profile intensity and polarizations (Stokes profiles) in terms of vector magnetic fields, and for mathematically extrapolating the measured photospheric field upwards into the corona.

At this time we do not have a predictive understanding of flare onset. Debates rage over the respective roles of magnetic flux emergence versus submergence, large-scale reconnection between flux system versus small-scale reconnection within them, and the importance of magnetic shear and high field strengths along magnetic neutral lines. In addition to the intrinsic scientific value of studying the configurations and processes that lead to solar flares, a thorough understanding of these processes is a necessary prerequisite to any serious attempt at flare prediction.

Energy Release and Transport Mechanisms

The other central questions in the study of solar flares concern the mechanisms by which the stored magnetic energy is released and the form that this released energy takes (accelerated particles, bulk heating, shocks, etc.). These questions can be approached in two distinct ways. First, theoretical models for the dissipation of magnetic energy (through, for example, reconnection) can be developed. Such an approach demands that the conditions (e.g., magnetic field geometry, density, temperature, degree of turbulence, etc.) in the energy release site be established prior to and during the energy release. Such information can come only from observations rich in spatial, spectral, and temporal detail. We note that the only images showing coronal sources with clearly resolved structures have been obtained with the sub-arcsecond resolution provided by large radio interferometric arrays. An arcsecond is also the order of the length scale associated with the collisional degradation of deka-keV electrons in plasma characteristic of the flaring corona. Such electrons are believed to be responsible for hard X-ray bursts. It is desirable, therefore, to obtain spectral information on hard X-rays with similar arcsecond spatial resolution.

In the second approach, the interrelated radiation signatures of the flare at several wavelengths can be interpreted through energy transport models, in order to place constraints on the form of the energy release process. In addition, analysis of the processes which transport the flare energy through the solar atmosphere is valuable in itself, even if the origin of the energy input is relegated to the role of a boundary condition. Much useful plasma physics can be learned through the study of, for example, the radiation signature of a relatively dense beam of nonthermal electrons as it interacts through both collisional and collective processes with the ambient plasma in a flare loop. The role of radiative energy transport in plasmas is a complicated subject, but one which is now being studied quantitatively in solar flares with sophisticated numerical techniques; the richness of the available spectral information in

ORIGINAL PAGE
COLOR PHOTOGRAPH

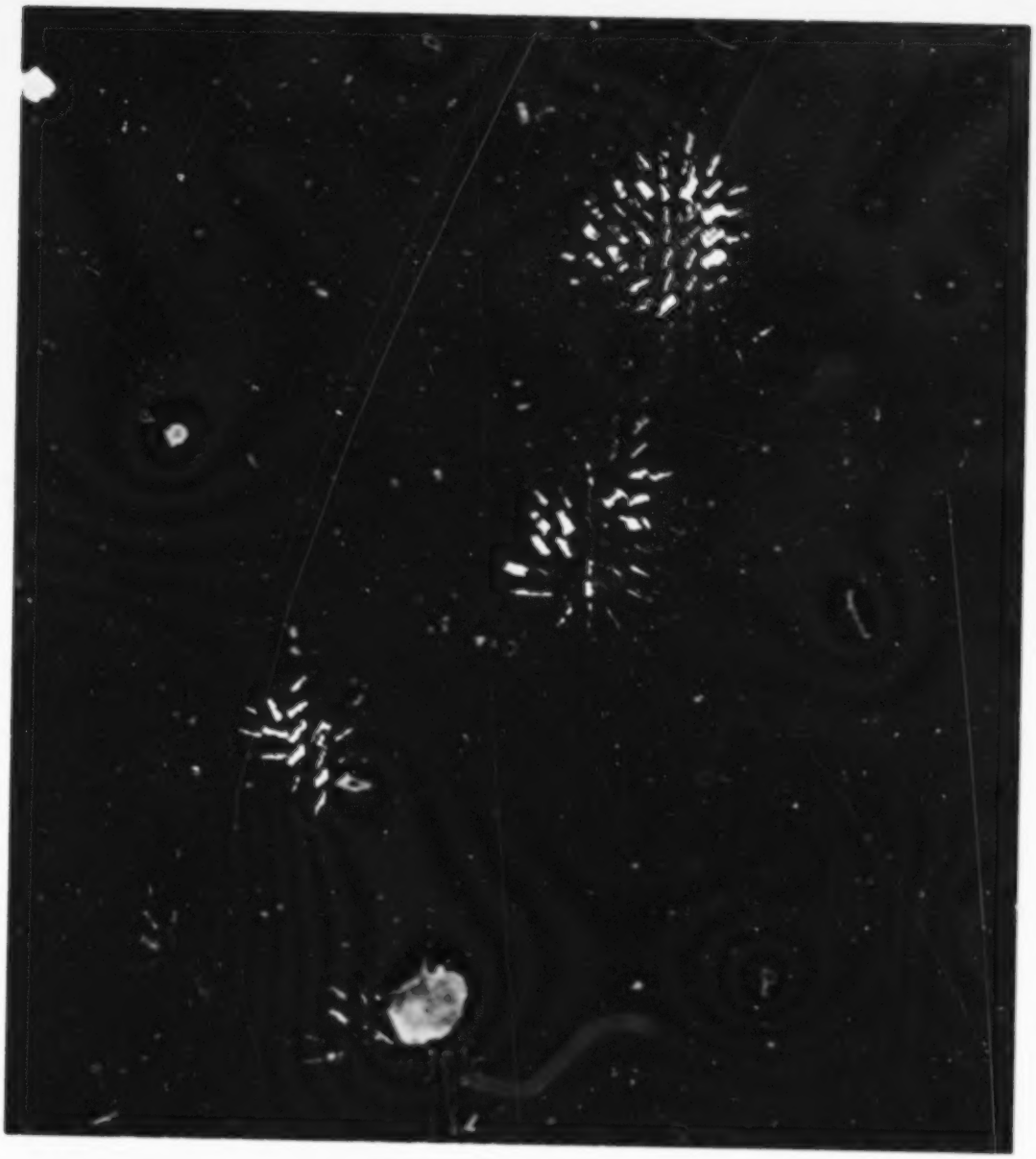


Figure 2. Vector magnetic field data from the Okayama Astrophysical Observatory (courtesy of M. Makita) obtained in the Fe I 5250 angstrom line for a solar active region on 1984 April 27. The region produced numerous flares, the largest being an X13/3B on April 24. The green lines in the figure are the calculated potential field lines extrapolated into the corona. They are superposed on the line-of-sight magnetic field shown in red for positive and blue for negative fields. The line-of-sight field is determined from measurements of the circular polarization and the transverse component, whose strength and direction are shown by the white line segments, is determined from measurements of the linear polarization. (From NASA CP-2374, "Measurements of Solar Vector Magnetic Fields," M. Hagyard, ed., 1985.)

solar flares makes it possible to pursue such studies to a level of detail impossible elsewhere. High spatial resolution optical and X-ray images and spectra can be used to study the role of mass motions in the flare energy balance. Simultaneous high-resolution optical, UV, and soft X-ray images and spectra can be used to infer the temperature structure of the flaring atmosphere, and hence the role of thermal conduction.

Theory and Modeling

Theory and modelling of radiative, thermodynamic, magnetohydrodynamic, atomic, nuclear, and plasma processes are essential components of an intellectually stimulating and vigorous Max '91 program. From a theoretical standpoint, we feel that the predictive power of much modeling so far, and consequently its usefulness in a comparison with observations, is severely restricted by the degree of sophistication and reality of the models. For example, the majority of models to date involve energy release, by unspecified mechanisms, in a separate "black box" (the so called "acceleration region") somewhere in the flare structure. A more physically realistic picture, in which the energy release and energy transport regions are unified into a self-consistent whole, can be achieved only if observations are available to provide guidance to the natural interrelationship of these regions.

Theoretical analysis of the energy release and transport processes has evolved significantly during the last solar maximum. This is a consequence of the development of large-scale, high-speed numerical techniques that can simulate the nonlinear evolution of a complex set of interrelated effects such as magnetohydrodynamics, radiative transport, and particle acceleration. As has already been demonstrated by studies carried out during the last solar maximum, such numerical studies can provide the link between observations throughout the electromagnetic spectrum, from radio waves to hard X-rays. We urge the continued development of such numerical studies as a complement to analytic modeling of the individual physical processes involved.

Atomic, Nuclear, and Plasma Physics

The interpretation of flare radiation signatures involves the application of both plasma and atomic physics. These fields of study have long enjoyed a symbiotic relationship with the study of solar flares themselves; not only do they permit us to better understand the nature of the flaring atmosphere, but also much can be learned through the study of solar flare soft X-ray and gamma-ray spectra about the relative abundance of chemical elements and about the atomic and nuclear parameters governing the flare radiation processes. These results can have far reaching implications for other fields of study, such as the constraints the solar helium abundance places on cosmological models.

Solar Terrestrial Effects

Solar flares have well known, but poorly understood, effects on the Earth's environment. Geomagnetic activity often results when a flare-associated ejection impacts on the magnetosphere. This has the following effects: increased energetic particle fluxes in the magnetosphere, increased ion density in the ionosphere, increased heating of the neutral atmosphere, aurorae, and even corrosion in long metal pipelines. The intense, high-energy particle fluxes associated with some flares endanger the health and even the lives of astronauts or cosmonauts when they are unprotected by the Earth's magnetic field, that is, when they are in high-inclination orbits or outside the magnetopause on lunar and planetary flights. These streams of energetic particles (electrons, protons, and neutrons) are ejected along open magnetic field lines in the flaring region. It is still a largely unanswered question just how these particles are accelerated on, or onto, such open field lines during the course of the flare. Knowledge of the detailed magnetic field structure of flaring active regions (both open and closed field lines) would clearly be invaluable in such an investigation, which in turn would provide insight into the mechanisms of particle acceleration and transport in the flare, and would ultimately improve our ability to predict such events.

To address the issues discussed above requires observations of flare phenomena with higher spatial, temporal, and spectral resolutions than have hitherto been available. Since the last solar maximum, instrument technology has been developed with the potential to reach new physically significant thresholds. In the following section, we discuss a coordinated observing program for the next maximum that involves advanced instruments on spacecraft, balloons, rockets, and at ground-based observatories.

REQUIRED OBSERVATIONS

From the scientific discussion given above, it is clear that breakthroughs in our understanding of solar flares will depend critically on a coordinated set of observations spanning the electromagnetic spectrum. Some of the observations will be made from spacecraft currently being built and from already existing ground-based telescopes, but the scientific objectives identified for Max '91 cannot be achieved without the advanced instrumentation on balloons and the new generation of instruments on the ground.

We begin this discussion of the required observations with brief descriptions of the spacecraft that are expected to be in orbit during Max '91 and that will have significant solar flare capability. Even though there will be no new NASA spacecraft dedicated to the study of solar flares, it is hoped that the Solar Maximum Mission spacecraft (SMM) can be kept operating at least until 1991. The prime new spacecraft are Solar-A, an ISAS (Japan) spacecraft, NASA's Gamma-Ray Observatory (GRO), and the Global Geospace Science (GGS) program. Solar-A and GRO are officially approved, and GGS is in the NASA FY '88 budget, so that there is a high probability of successful observations from all three programs. Details of the instrumentation on these spacecraft appear in Appendices A and B.

There are also several other space programs for which there is some small probability of deployment during the next maximum. These range from rockets and Spartans, which will indeed fly in some form, to any of several proposed missions that may or may not fly. Among the strongest possibilities are instruments on NOAA meterological satellites and Department of Defense missions. We summarize some of these briefly in Appendix B.

Of the three approved programs, only Solar-A, with its models 115-kg payload and very limited telemetry capability, contains instruments specifically designed for solar flare research. These include a hard X-ray imager that will extend the energy range well above the 30-50 keV limit of SMM and Hinotori, and a soft X-ray imager provided by a U.S. team, plus X-ray and gamma-ray spectrometers. Since the Japanese have launched their previous spacecraft on schedule, we can confidently expect observations to begin shortly after the scheduled launch date in August, 1991.

GRO is noteworthy for its broad energy range extending from 15 keV to 20 GeV, and its extreme sensitivity which is both an advantage for the weakest flares and a disadvantage for the more intense events. It will certainly produce a large number of solar observations that will be valuable for flare research in spite of the lack of imaging and high spectral resolution capabilities. Action needs to be taken to ensure that these data are well utilized for solar physics.

The WIND and GEOTAIL spacecraft that form part of the GGS program will both carry energetic particle and plasma instruments for the detection of solar particles from plasma energies to several hundred MeV. In addition WIND will carry a low-frequency radio instrument that will track type II and III radio bursts from the high corona to interplanetary medium. Both of these spacecraft are scheduled for a 1992 launch.

The program described in this report aims at coordinating these space observations with data obtained from powerful new balloon, rocket, and ground-based instrumentation.

Balloon Observations

High-altitude balloons offer the capability of making unique observations in areas that address several of the basic questions of flare physics discussed in the previous section. High-quality observations can be made of energetic photons that can penetrate the upper layers of the Earth's atmosphere and of optical photons free of the seeing effects of ground-based observations. Furthermore, long-duration flights provide the long observing periods required to catch the infrequent large X-ray and gamma-ray flares. ***Consequently, in order to take advantage of the advanced diagnostic potential of long duration balloon payloads, we strongly recommend a major commitment to scientific balloooning at the next maximum.***

The basic questions of solar flare physics can be addressed most effectively from balloons with hard X-ray, gamma-ray, and optical imaging, spectroscopy, and polarimetry. The scientific objectives of observations in each of these areas are described in the following section, together with the exciting results that can be expected during the next solar maximum. Examples of instruments with the required capabilities that already exist or that have been proposed for baloon observations are described in Appendix C. ***In order for these instruments to be ready for the first flights in 1991, it is essential that they be selected and funded as soon as possible.***

High-Spatial-Resolution Hard X-Ray and Gamma-Ray Imaging Spectroscopy

Hard X-ray imaging observations have long been recognized as a key to understanding the processes of energy release and particle acceleration in solar flares. This is because the X-rays provide the most easily interpreted information about the high-energy electrons produced in a flare. The bremsstrahlung X-rays are produced before the available information about these flare processes is lost as the electrons lose their energy and are thermalized in the ambient atmosphere. Consequently, studying the temporal and spatial evolution of the hard X-ray emission can potentially reveal the site of the energy release and the fundamental nature of the acceleration process itself.

The primary objectives of hard X-ray and gamma-ray imaging observations during Max '91 are as follows:

- Identify the sites of particle acceleration and interaction.
- Study the temporal and spatial development of both the thermal and nonthermal electron components of solar flares.
- Locate the higher-energy nucleon component of strong solar flares.

To date, solar hard X-ray images have been limited to a resolution of 8 arcseconds and to energies below keV. Imaging during Max '91 will be possible from balloons with better than 2-arcsecond resolution and to energies in excess of 500 keV. Furthermore, the sensitivity of the new instrumentation will be at least 1,000 times greater than that of the Hard X-ray Imaging Spectrometer (HXIS) on SMM. Thus, the images will allow studies of flares to be made on the arcsecond size scales and the subsecond time scales that are comparable to the dimensions associated with the flaring magnetic structures and with the processes that modify the spectrum of the electrons producing the X-rays. These images will have such high spatial resolution that they will allow the propagation of the energetic electrons to be traced through the flaring region and the site of their acceleration to be identified.

As indicated in Figure 3, the high sensitivity and the possibility of 15-day balloon flights means that many flares can be detected and imaged per flight. Thus, ***a hard X-ray and gamma-ray imager with arcsecond angular resolution should be build and flown repeatedly on long-duration balloon flights during Max '91 in order, for the first time, to fully resolve flaring magnetic loops and trace the variation of the electron spectrum along them.***

High-Spectral-Resolution X-Ray and Gamma-Ray Spectroscopy

Significant advances in our understanding of the acceleration of electrons and ions in solar flares can be expected during Max '91 through new high-resolution spectroscopy of hard X-ray and gamma-ray continuum and gamma-ray line emission. Measurements with keV energy resolution will provide a qualitatively new window on these processes since essentially all the nuclear gamma-ray lines and many of the important hard X-ray continuum features are unresolved by present spacecraft spectrometers.

The primary objectives of such high-resolution spectroscopy during Max '91 are as follows:

- Determine the spectrum and angular distribution of accelerated protons from nuclear gamma-ray line intensities and shapes.
- Measure chromospheric abundances from gamma-ray line fluxes.
- Determine the temperature and density of the positron annihilation region from the width of the 511-keV line and the intensity of the 3-photon continuum.
- Separate the thermal and nonthermal components of the X-ray continuum emission and determine the shape of the electron spectrum.

Balloon-borne instruments using actively-shielded high-purity germanium (HPGe) detectors can measure photon energies between 15 keV and 20 MeV. When they are cooled to liquid-nitrogen temperatures, they have a spectral resolution of a few keV, a factor of about 50 better than the NaI(T1) scintillation spectrometers flown in space up to the present time. As shown in Figure 4, this high resolution is sufficient to make the first ever accurate measurement of all parameters of the expected gamma-ray lines with the exception of the neutron-capture deuterium line. The high resolution also allows the very steep (E^{-11}) spectrum of the superhot component to be measured and separated from the higher-energy power-law component. Several flares large enough to permit accurate line and continuum spectroscopy can be expected during a 15-day balloon fight. Consequently, ***a hard X-ray and gamma-ray spectrometer with keV energy resolution should be built and flown repeatedly on long-duration balloon flights during Max '91 in order, for the first time, to resolve the nuclear gamma-ray lines and determine their widths and Doppler shifts, and also to clearly separate the thermal and nonthermal components of the continuum X-ray spectrum.***

Sensitive High-Energy X-Ray Polarimetry

The primary question that can be addressed with a hard X-ray polarimeter is of fundamental importance in understanding the flare energy release process. The question is whether or not the electrons that produce the X-rays are beamed during the acceleration process, i.e., whether or not the acceleration process results in an anisotropic velocity distribution. If the electrons are beamed, then the resulting X-ray emission is expected to be highly polarized; if the electron velocity distribution is isotropic, then very little polarization is expected. Polarimetric data would provide electron beaming information on each individual flare without recourse to data from other flares. This is in contrast to the recently reported statistical evidence for electron beaming at higher energies based on the preference for gamma-ray flares above 10 MeV to be observed close to the limb.

Previous solar flare X-ray polarization measurements have failed to find evidence for polarization at the few percent level, but they have been limited to energies below ~20 keV, where thermal emission is known to dominate. It is now possible to design and build an X-ray polarimeter with the required factor of about three improvement in sensitivity to detect and reliably measure the polarization predicted by current theoretical models. Such a detector would extend the polarization measurements to higher energies, at least to 100 keV, thus

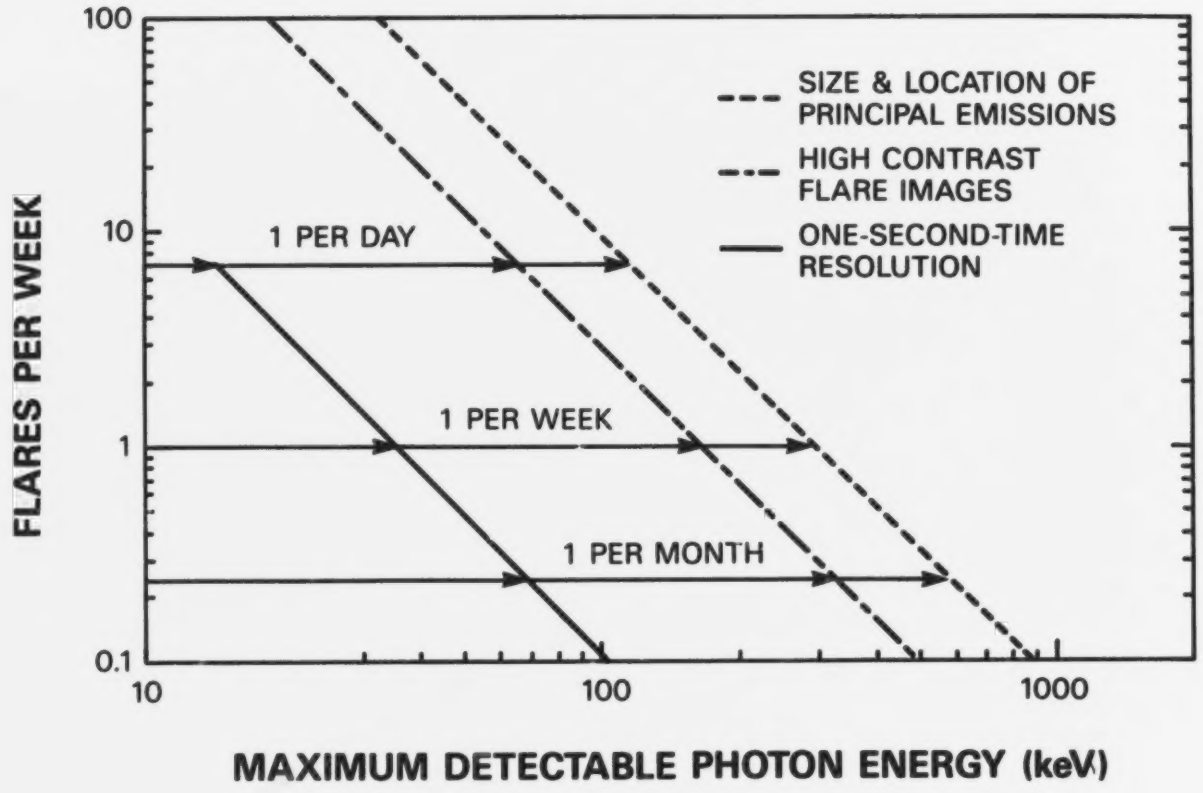


Figure 3. Plot of the expected flare rates during solar maximum as a function of the highest detectable hard X-ray energy for a possible balloon-borne imager. The solid line indicating the highest flare rates applies to flares for which the basic size and location of the principal hard X-ray emissions could be determined. The central broken line indicates the rates of flares for which high contrast flare images could be obtained. The lower solid line indicates the rates of flares for which such images could be obtained with unprecedented one-second temporal resolution.

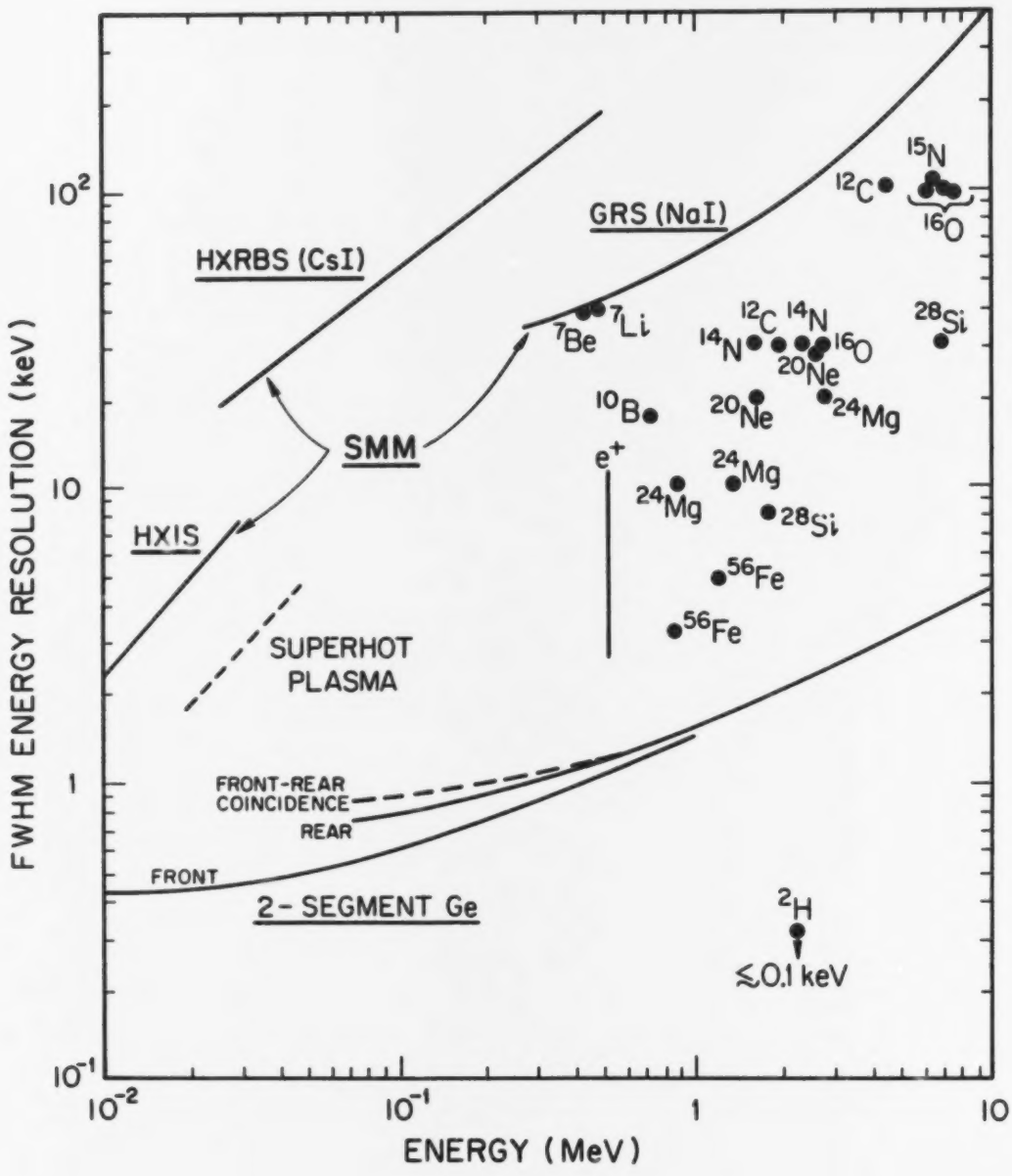


Figure 4. The spectral resolution as a function of photon energy for a two-segment HPGe detector is compared to the resolutions of the hard X-ray and gamma-ray spectrometers on SMM. The typical widths expected for gamma-ray lines in solar flares are also shown. Note that none of these lines were resolved with the Gamma-Ray Spectrometer (GRS) on SMM but all except the neutron-capture deuterium line at 2.223 MeV with a predicted width of <0.1 keV will be resolved with a cooled HPGe detector. Similarly, the broken line indicating the energy resolution to resolve the spectrum from the superhot plasma at a temperature in excess of 30×10^6 K shows that this component was not resolved with the SMM instruments but can be clearly resolved with a cooled HPGe detector.

avoiding the thermally produced softer X-rays, which are expected to be polarized at a very low level by backscattering in the dense solar atmosphere. Several flares large enough to allow accurate polarization measurements down to the few percent level could be detected during a 15-day balloon flight. ***A sensitive hard X-ray polarimeter should be built and flown repeatedly on long-duration balloon flights during Max '91 in order to establish, for the first time, the degree of beaming of accelerated electrons and to distinguish between thermal and nonthermal electron distributions.***

High-Resolution Optical Imaging and Polarimetry

High-resolution optical imaging on balloon flights was achieved by Project Stratoscope in the late 1950's, and has been exploited since then by German, Russian, and Japanese groups for additional white-light studies. Balloon flights would produce our first views of active region magnetic fields at a resolution approaching the size of the basic flux tubes themselves.

The primary objectives of balloon-borne optical polarimetric imaging during Max '91 are as follows:

- To measure vector magnetic and velocity fields in the solar atmosphere with much better spatial resolution and for much longer time intervals than can be achieved from the ground.
- To measure the buildup and release of magnetic energy in active regions over periods of several days.
- To study the magnetic field changes associated with transient events such as Ellerman bombs, flares, and flux emergence.
- To detect and classify wave modes on fine spatial scales in the photosphere and chromosphere.

Observations at balloon altitudes would enable the intensity, magnetic, and velocity fields in the photosphere and low chromosphere to be studied free of atmospheric disturbances. A spatial resolution of 0.5 arcsecond could be achieved, compared with ~1-2 arcseconds on the ground, and a stability of 0.01 arcsecond would be possible, some 30 times better than on the ground. Consequently, ***an optical imaging polarimeter should be flown repeatedly on high-altitude balloons during Max '91 to measure quantitatively, for the first time, the energy content of active regions before, during, and after flares through the measurement of the vector magnetic and velocity fields.***

Long-Duration Balloon Capabilities

Long-Duration Balloon Flights (LDBF's) provide the opportunity for 15 to 20 days of observations so that, during solar maximum, several large flares and many smaller ones can be expected. Large, powerful instruments, up to ~2,000 lbs total payload weight, can be carried by the present standard 28.4 million cu ft balloons to altitudes of ~130,000 ft (40 km). At that altitude there is less than 3 g cm^{-2} of overlying atmosphere, so that hard X-ray and gamma-ray measurements down to ~15 keV are possible. Diffraction-limited optical observations free from atmospheric disturbances are also possible.

LDBF's have the following additional advantages for solar observations:

- Accessibility and low costs compared to instruments in Earth-orbit.
- Continuous observing periods of ~12-hours duration (even longer for Antarctic flights).
- A benign launch and flight environment.
- Rapid turnaround with opportunities for repairs and upgrading between flights.
- Low and very stable radiation background.
- Simple liquid-nitrogen cooling for cryogenic detectors.

For standard zero-pressure balloons, the temperature of the gas, and therefore the balloon altitude, is controlled by the radiation received from the Sun and the Earth. Thus, the balloon floats at high altitude while it is heated by the Sun but drops at night. If the balloon initially reaches a high daytime float altitude, it will normally remain above the tropopause in its day-night excursions. Then, in this simple RAdiation COntrolled balloON (RACOON) mode, flight durations are limited only by gas losses, which can be offset by ballast drops, and by balloon lifetime.

LDBF's in the RACOON mode can provide 15 to 20 days at float altitude by circumnavigating the globe. During the three-month summer season at midlatitudes, strong stable zonal winds flow with high velocity approximately along latitudinal lines, so circum-global flights are feasible. At present, for political reasons, around-the-world flights are possible only in the southern hemisphere. Trans-Pacific flights from the U.S. to China, however, can offer 5- to 10-day durations in the northern summer, as well as opportunities for collaborations with China and Japan. In addition, LDBF's are possible year-round at equatorial latitudes, provided adequate launch and recovery sites can be found. LDBF's from Antarctica in summer would have the added advantages of continuous sunlight for 24-hour coverage and perhaps continous telemetry to a single ground station. However, since the Sun would be low in the sky, antarctic LDBF's would probably be limited to photon energies $\gtrsim$50 keV. ***It is important that all of these alternate launch sites and flight paths be investigated, particularly in the northern hemisphere, to allow each of the instruments at least two flights per year.***

LDBF's with heavy payloads have been pioneered by solar physics and cosmic ray groups with three successful flights

lasting between 6 and 18 days from Australia. While the present balloon capabilities are adequate for many solar observations, it is clear from these flights that, ***in order to ensure the success of LDBF's during the next solar maximum, it is essential that their reliability be improved and the capabilities expanded, particularly in the areas of autoballasting, command, telemetry, navigation, and power.*** Appendix D describes the current LDBF capabilities and the required improvements.

Ground-Based Observations

The very nature of solar activity requires the simultaneous observation of temperature regimes from a few thousands to tens of millions of degrees, in addition to nonthermal processes. The observations must then necessarily cover a wide range of wavelength regimes, some of which can best be conducted from the ground. In particular, optical, i.e., visible light, observations uniquely delineate the morphology, evolution and nonpotential character of magnetic structures in the photosphere and chromosphere, and so measure the magnetic energy buildup prior to flares, as well as the transport of energy in thermal and nonthermal form from the corona to the chromosphere and photosphere. Radio observations extend this magnetic field measurement ability to coronal levels and provide a sensitive technique for observing high-energy electrons as close as possible to the site of their acceleration.

Dedicated vs. Nondedicated Facilities

For ground-based studies of solar activity, an important distinction should be drawn between dedicated and nondedicated facilities. Dedicated facilities have as one of their primary goals the study of solar activity and, as a consequence, their observing schedule, scientific program, hardware, and software are optimized accordingly. Nondedicated facilities, such as the National Solar Observatory at Sacramento Peak (with its broader solar objectives) and the VLA, have demonstrably superior hardware which enables them to make important solar flare observations. However, the very breadth of their missions impose serious limitations in their application to solar activity studies. In particular, the flexible scheduling of observing time at these facilities is difficult, but is essential for solar activity studies. ***The duration, unpredictability, and simultaneous broad spectral requirements of solar activity demand dedicated ground-based facilities for its study.***

Optical Magnetic Field Observations

Throughout the last solar maximum, research-quality line-of-sight magnetograms of the full Sun were obtained on a daily basis at only one site: Kitt Peak National Observatory. These data have high spatial resolution (1-arcsecond pixels) and continuity over a full solar cycle, and they are readily available in Solar Geophysical Data and the SMM databank. Consequently, they have proved to be extremely valuable, in spite of their relatively low frequency of typically one full solar image per day (weather permitting). Over 100 papers were published based on these data.

Magnetograms were obtained of selected active regions rather than of the full Sun, using the video magnetograph at Big Bear Solar Observatory. This instrument's unique strength is its combination of high temporal resolution (15 image pairs per second) and high spatial resolution ($\sim$1 arcsecond pixels). During the last solar maximum, it was the key to the discovery of a relationship between flare occurrence and magnetic flux cancellation. Is this cancellation due to emergence or submergence of flux tubes, or is it due to magnetic reconnection? Our present knowledge is based on only a week's data during the decay phase of a single active region, so more observations are obviously required to clarify the physical nature of these fundamental processes over a variety of solar flare sizes and types.

The understanding of how magnetic flux emerges and disappears, and how it drives and triggers magnetic reconnection and particle acceleration, are so central to flare physics during the next maximum that a second dedicated longitudinal magnetograph is required to ensure the availability of magnetograms of selected active regions, with high temporal and spatial resolution, for the largest practical fraction of all flares. ***A second high-resolution dedicated longitudinal magnetograph should be placed in synoptic operation throughout the next solar maximum in order to ensure an adequate database for understanding the role of magnetic flux emergence and cancellation in the flare energy release process.***

Optical Vector Magnetic Field Observations

During the last maximum, measurements of vector magnetic fields emerged from a level of instrumental inadequacy to one in which some measurements had to be taken seriously as significant, if not fully precise, physical measurements. The sole vector magnetograph capable of serious flare research during the last solar maximum is at Marshall Space Flight Space Center (MSFC). However, it is the only such dedicated vector magnetograph, and its observing site is meteorologically far from ideal. For these reasons, timely vector magnetograms have been available for only a small fraction of flares and active regions during the past solar cycle. The unique feature of the Marshall instrument is its ability to observe simultaneously over a large field of view (5 arcminutes), albeit at relatively low spatial resolution (3-arcsecond pixels). It can obtain simultaneous images of a whole active region, thus allowing measurements to be made with minimum observational distortion of the spatial derivatives that are required to determine the current from the curl of the vector magnetic field. Furthermore, with this instrument magnetograms can be obtained in a short enough time (typically 6 minutes for the minimum data set) to be insensitive to changing solar conditions and less than ideal observing conditions. Among its many

important results is the demonstration that the flare probability of an active region is closely related to the magnetic field configuration in the vicinity of the neutral line that divides regions of opposite polarity.

At the next maximum, vector magnetic field measurements promise to contribute the central observational component of several aspects of flare physics:

- The three-dimensional magnetic morphology at sites of particle acceleration and bulk energization.
- The relationship between active-region magnetic fields and coronal structures.
- The locations and amplitudes of currents in active regions.
- The energy content of active regions and its relationship to flare occurrence.

Two new instruments are presently being designed for measurements of vector magnetic fields, but neither of them, even if they are successfully placed into operation, will be dedicated to flare and active region measurements throughout the next maximum. Current plans call for both these instruments to be available for shared use at the National Solar Observatory at Sacramento Peak for some modest fraction of the next solar cycle. First, at High Altitude Observatory (NCAR), a new Stokes profile spectrograph is being developed. It will make polarimetric line profile measurements of unprecedented spatial and temporal resolution, at the expense of spatial simultaneity over a two-dimensional field of view. Although this design approach may not be ideal for making vector magnetograms for flare studies, this instrument will be a powerful tool for the complex interpretive task of inferring vector magnetic fields from Stokes line profiles. Second, a prototype vector magnetograph for use in space is being developed at the Johns Hopkins Applied Physics Laboratory, with funding from the U.S. Air Force. This instrument is a testbed for technological innovation with the objective of developing the first vector magnetograph to be flown in space. In addition to one year of shared operation at the National Solar Observatory, it may be considered for long-duration balloon flights in the future.

The objectives of understanding how and where flare energy is stored, and what causes its release, are central to the flare physics of the next maximum. A second dedicated vector magnetograph, at a high quality site far from the existing instrument at MSFC, is required to ensure the availability of vector magnetograms for the largest practical fraction of both ground- and space-based flare observations. It is equally important that there be a second dedicated magnetograph to provide confirmation of the results that is so essential for these very difficult measurements. ***A second dedicated high-resolution vector magnetograph should be in synoptic operation throughout the next maximum in order to ensure the largest practical observational database for both predicting solar flares and understanding how their energy is stored.***

Optical Imaging Spectroscopy

The last maximum saw a renaissance in flare spectroscopy, as a result of the first application of charge-coupled devices (CCD's) to solar flare Hα line profile measurements. Although spatial resolution (2 – 3 arcseconds) and a temporal resolution (10 to 15 s) were both modest by imaging standards, the addition of spectral information to the images provided evidence of the following phenomena:

- Injection of energetic electrons into the lower atmosphere.
- Explosive evaporation of the upper chromosphere.
- Shocks driven both upward and downward during the impulsive phase.
- The role of both energetic electron streams and heat conduction in the production of the X-ray flare plasma.
- Momentum balance of upflowing and downflowing plasmas.

The required observations were possible only infrequently, since the observational capability for making imaging spectra was present only at the Vacuum Tower Telescope of the National Solar Observatory at Sacramento Peak. As a result, combined space- and ground-based spectral data were obtained for only a few small flares, and the conclusions are therefore very limited and speculative.

What is needed during the next maximum is the ability to make spectroscopic observations of the maximum practical number of major flares. ***A dedicated imaging spectrograph should be in synoptic operation throughout the next maximum in order to ensure an adequate database for identification of the morphology, preflare thermodynamics, and intensity of energetic electron precipitation at the unique footpoints of those magnetic structures in which nonthermal electron acceleration takes place.***

Microwave Imaging Spectroscopy

Observations of microwave emission hold the promise of direct measurement of coronal magnetic field strengths associated with the preflare active region, the nonthermal flare-accelerated electrons, and the thermal flare-heated plasma. A highlight of the past solar maximum has been the high-resolution images made possible by such large interferometers as the VLA. An example is shown in Figure 5. Images such as this accurately locate the field-weighted emission of nonthermal electrons that may be from the same population of electrons that produce the hard X-rays. The regions of strong

ORIGINAL PAGE
COLOR PHOTOGRAPH

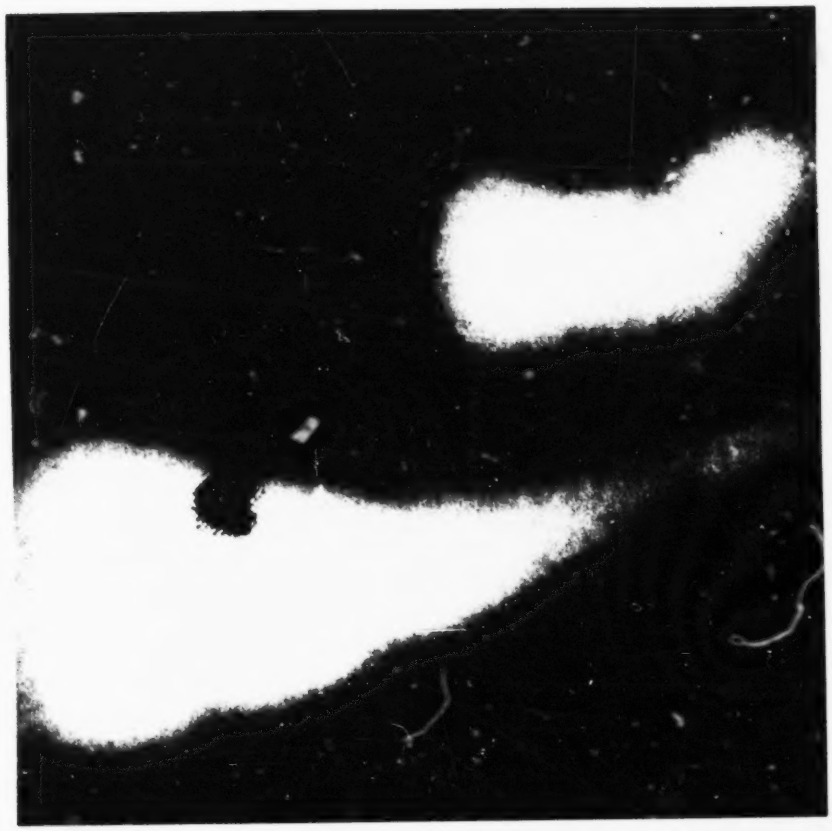


Figure 5. A 15 GHz microwave image taken with the VLA superimposed on an Hα photograph taken at the same time at the Big Bear Solar Observatory. The microwave emission shows up as blue blobs on two lines joining the two bright Hα regions shown in white. It is believed that the microwave emission is synchrotron radiation from electrons with $\gtrsim$100 keV spiralling in magnetic loops with footpoints in the Hα ribbons. The picture covers a 30-arcsecond (2.2×10^4-km) square on the solar surface during a flare on 23 March 1980. The microwave image has an angular resolution of 0.5 arcseconds.

coronal fields are located in the context of photospheric and chromospheric structures measured optically.

In general, however, microwave imaging did not fulfull its potential as a powerful diagnostic of nonthermal electrons, coronal fields, and thermal plasmas. The reason for this is that the VLA was able to observe at only four widely spaced frequency bands, whereas the diagnostic content of solar microwave emission requires spatially resolved observations with ~ 10% spectral resolution. Although the present Owens Valley facility has the requisite spectral coverage and spatial resolution, it lacks the number of baselines to image all but the simplest solar sources. ***Observations that combine high spatial and spectral resolution are essential to exploit microwave diagnostics of coronal fields, energetic electrons, and pre and postflare plasmas.***

To improve upon the VLA's demonstrated ability to provide high-resolution, solar imaging, a number of developments would be of particular value during the next solar maximum:

- Full implementation of the P-band capability for high-resolution imaging of decimetric phenomena.
- Improved operational and scheduling flexibility.
- Improved calibration for solar observation.
- Improved time resolution (to 52 ms) for transient phenomena.

Dekametric, Metric, and Decimetric Observations

At lower frequencies, radio observations can document large-scale density structures and nonthermal electrons in the middle and upper corona. Because the emission frequency is usually equal to or twice the plasma frequency, spectral data provides a good indication of the vertical characteristics of shock waves and electron beams that stimulate the wide range of transient emissions that have been observed. In the last solar maximum, this capability was enhanced by imaging observations at Clark Lake, Culgoora (Australia), and Nancay (France). For the coming maximum, there is a grave danger of losing this essential capability since Culgoora has been dismantled, Clark Lake is unfunded for solar observations, and Nancay operates only over a limited range of frequencies. This loss creates a missing link in observing the causal chain connecting solar flares to their terrestrial effects. ***Dekametric, metric, and decimetric imaging and spectroscopy are essential if we are to form a comprehensive view of solar activity.***

The Radio Solar Telescope Network (RSTN) operated by the Air Force provides continuous monitoring of the Sun at discrete radio frequencies extending from 245 MHz to 15.4 GHz. Systematic archiving of these observations in computer-accessible form will make this dataset useful both for statistical studies of many events and as a supplement to detailed observations of specific events.

Decimetric and metric radio observations of interplanetary scintillations can extend the analysis of flare effects to the solar wind by imaging interplanetary disturbances up to and even beyond the Earth. Interplanetary scintillation measurements of disturbances in the solar wind are currently being made in Japan, India, and the U.S., and daily maps of disturbances are expected to be available from Indian and English observations during the Max '91 period. The observations show the transport of solar flare effects to the Earth and enable research to be carried out in the physical processes controlling that transport.

Synoptic Observations and Analysis Facilities

During the previous solar maximum, the usefulness of many data sets for systematic studies of solar activity was severely constrained by their analog nature. Examples of such underexploited data sets include photographic Hα and white light images, and film-based dynamic radio spectra. (In contrast, the digital form of such data sets as Mount Wilson magnetograms has enabled them to be very productively reanalyzed in response to new developments.) Therefore, to effectively exploit such data during the coming solar maximum, ***the essential synoptic data must be acquired in digital form.***

As a corollary, ***digital data analysis equipment must be provided so that research groups can process digital images rapidly and economically, thereby facilitating the physical understanding of digital imaging data.*** The equipment will also simplify the exchange, coordinated analysis, and interpretation of diverse data sets and, by the application of image enhancement techniques, will improve the effective quality of individual data sets. The most important items are (1) high throughput imaging workstations at every site that handles digital data, and (2) video disk players when the data analysis requires the interpretation of sequences of images in movie form.

Other Observations

Although the shuttle program is on the road to recovery, access to space in the 1991 to 1994 timeframe is likely to be very limited, and the only means for observing in the UV and XUV will be from sounding rockets. Although observations from such rockets are brief, they can provide valuable information such as high-resolution images and spectra to determine the preflare and thermal-phase geometry and physical conditions. Consequently, we endorse the continuing support of the sounding rocket program during Max '91 as an essential element of solar physics research.

The current inventory of rocket-borne instruments includes high-resolution spectrographs covering the UV (120 - 170 nm), various bands in the EUV (20 - 120 nm), and in the soft X-ray (1 - 20 nm) region of the spectrum; UV and visible coronagraphs; high resolution UV filtergraphs (120 - 200 nm); and soft X-ray and EUV telescopes. Existing research

programs include studies of active regions, solar wind origin and behavior, the quiet and active corona, and a host of other topics. Although serendipity obviously plays a major role, a number of flare observations have been made from sounding rockets in the past, though such campaigns are not easy to plan or to execute.

Several recent technical developments have greatly enhanced the potential for making significant new observations from rockets. These include the following examples:

- The development of multilayer mirror technology now permits us to make narrow-band soft X-ray observations with normal-incidence optics.

- Coronal loops have been observed in the Si XII lines at 4.4 nm in a recent demonstration experiment, and a payload is currently under development that will photograph the corona in Fe XVI (6.7 nm) with sub-arc-second resolution.

- Large-format high-resolution CCD detectors (up to 2,000 x 2,000 pixels of less than 20-micron size) are being developed by several companies for commercial applications, making them relatively inexpensive and available.

- UV interferometry (down to 155 nm) is now feasible, and at least one high-resolution filtergraph is being developed for C IV observations.

- New advances in diffraction grating design have made possible the development of soft X-ray spectrographs that are stigmatic, making them faster by two or more orders of magnitude.

- The development of the Aries sounding rocket, whose payload compartment is over a meter in diameter, makes it possible to carry a cluster of several instruments and will allow a comprehensive set of observations to be made on a single flight.

COORDINATION OF OBSERVATIONS AND ANALYSES

Coordinated flare data are far more valuable than an equal amount of data obtained in random ways on random events. Such data sets allow multiple, complementary analyses of various aspects of single events or single periods of data. Since an "average flare" is rather poorly defined, and certainly does not correspond to any actual event, comparison of radiation signatures at a variety of wavelengths is meaningful only if they pertain to the same flare event. Consequently, ***to obtain the greatest scientific return during the next solar maximum, we propose a Max '91 program for the coordination of observations and analyses.***

The key to the Max '91 program would be an individual solar physicist to act as the "Max '91 Coordinator." He or she would become familiar with the capabilities and plans of observers worldwide, and would distribute this information to all interested parties. In addition, the Coordinator would establish communications paths around the world and would act as the primary node of an information network, receiving, evaluating, and appropriately relaying information of potential interest to participating scientists. A calendar of observing campaigns and other upcoming events would be maintained and distributed. Solar activity forecasts would be provided to observers worldwide, as was done for ground-based and space-based observers during the Skylab, Spacelab 2, and SMM space missions.

While the goal of many of the instruments at the next maximum is to be able to make observations of flares no matter where they occur on the solar disk, flare prediction will be vital during observing campaigns involving many different types of instruments with different fields of view. The accurate prediction of the probable frequency, nature, and location of flares will be particularly important for selecting active regions of interest to satisfy previously agreed-upon objectives. Such prediction is routinely done at the Space Environment Laboratory (SEL) at NOAA in Boulder, Colorado. White-light observations of sunspots and magnetic classifications of active regions from the Air Force Solar Optical Observatory Network (SOON) sites are essential to accurate flare prediction, as are images of longitudinal and vector magnetic fields. During the last maximum, the SOON Hα images proved to be invaluable in aiding with the interpretation of other flare observations. They need to be continued at the highest possible repetition rate to maximize their usefulness during Max '91.

International Programs

International participating in the Max '91 program is essential if the greatest benefit is to be derived from the plan outlined in this document. Solar physics has a strong international flavor at all times (e.g. the leading journal in the discipline is published in The Netherlands), but a program of the scope and nature planned for the Max '91 period is international by its very nature. For example, spacecraft and long-duration balloons fly over many nations during their flights, and they observe the Sun at different longitudes. Consequently, acquisition of ground-based solar data, cotemporal with spacecraft and balloon observations, requires the cooperation of many observatories around the world. Long-duration balloon flights also require international agreements because of the different countries that are overflown.

Many countries have active solar physics research programs, and vigorous participation by a large group of international scientists will greatly enhance the Max '91 research effort, both observationally and theoretically. State-of-the-art solar radio observations are made routinely in Brazil, China, France, Germany, Japan, Russia, Switzerland, and the U.S., at least. Flare theorists contribute from Argentina, Australia, Britain, Italy, Japan, The Netherlands, the U.S., and many other countries. On NASA's Solar Maximum Mission alone, the following countries are represented by Principal or Co-Investigators: Argentina, Britain, France, Italy, The Netherlands, Poland, the U.S., and West Germany. Japan plans to fly the Solar-A spacecraft dedicated to solar observations with a U.S.-provided instrument on board, and the Soviets plan a vigorous space program during the MAX '91 era. High-quality ground-based observations are made in countries too numerous to mention, and there is a long-standing tradition of making the data available to foreign colleagues. Clearly, ***the existence of a strong and coordinated international effort at the next solar maximum will ensure the most effective and rapid advance in our understanding of solar activity processes.***

The highly successful SCOSTEP-sponsored programs carried out during and after the previous solar maximum serve as a valuable precedent to guide our planning for the next maximum. They include the Solar Maximum Year (SMY), lasting two and a half years, and the Solar Maximum Analysis (SMA) period, lasting four years. These programs had an overall leader, an advisory committee, and topical teams with leaders; participants and leaders were chosen from the international solar physics community. Observational and analytical results were presented at Workshops in Europe, Asia, and the U.S., and at symposia held in conjunction with COSPAR meetings.

Following this precedent, it is suggested that the international program of FLAre RESearch at the maximum of Cycle 22, to be called FLARES 22, become a program of SCOSTEP, perhaps fitting into the existing Solar-Terrestrial Energy Program (STEP). It should have an overall leader of international stature, and topically focussed subprograms should be identified and leaders designated. ***The FLARES 22 observing program should include a series of campaigns during a***

four-year interval beginning in 1991. The campaigns would be driven by solar activity and events such as long-duration balloon flights or specified Carrington rotations. The data acquisition program should be followed by a FLARE 22 analysis program lasting an additional three years during which a mix of small topical workshops and larger general meetings would be organized.

It is highly desirable to coordinate the FLARES 22 program with the International Space Year that will begin in 1992, the International Solar-Terrestrial Physics program, and the plans of the Inter-Agency Coordinating Group (ESA, NASA, ISAS, and Intercosmos) to make solar-terrestrial physics its next area of emphasis. These coordinations are yet to be worked out, however.

PROGRAM PLAN

The keys to innovative and successful flare research during the next solar maximum are the instrument developments, coordinated observations, and multispectral data analyses. As described in previous sections, the dramatic increase in physical understanding to which we aspire with the Max '91 program can come only from integrated data adequately covering the entire electromagnetic spectrum and obtained using a diverse set of instruments on spacecraft, balloons, and rockets, and on the ground. Consequently, the planning and coordination of these multifarous activities must be a central feature of the Max '91 program if it is to achieve its goal of the maximum increase in our understanding of solar flares within the budgetary and programmatic constraints.

The program plan of the Max '91 effort can be divided into three phases:

Phase I: Planning and Instrument Development

Phase II: Coordinated Observing and Specialized Campaigns

Phase III: Analysis and Interpretation

There will inevitably be overlap among these three phases, but their timing is dictated by the solar cycle itself. The plot on the front cover of this document showing the predicted sunspot numbers during Cycle 22 suggests that, while the peak is expected in 1991, significant increases in activity can be expected as early as 1989. More significant indicators of flaring activity are shown in Figure 6, where the numbers of optical, X-ray, and proton flares that were observed during the last maximum are plotted for the years before and after the time of maximum sunspot number. The X-ray plot shows that the number of flares becomes high one year before the maximum and is actually the greatest in the three years following the year of the maximum. The numbers of optical flares and the more terrestrially-significant proton events show similarly skewed distributions.

On the basis of these data, the launch date for Solar A, and a realistic assessment of when the new, more sophisticated balloon-borne and ground-based instruments can be readied for observations, we conclude that the phase of coordinated observations should start no later than 1991 and that its duration should be four years. Earlier test flights of the balloon instruments and the first observations with the ground-based instruments should be planned for 1989 and 1990. This schedule is very tight, but the ultimate reality is that the solar cycle marches inexorably on, and hence, planning and instrument development must start as soon as possible.

The Max '91 Steering Committee consisting of the group of scientists responsible for this report is in existence now, and is prepared to remain so throughout the Max '91 Program. It is prepared to take on the responsibility of providing guidance in defining and leading both the program as a whole and its components. It is similarly prepared to assist the funding agencies with the incorporation of new instruments into the overall program and with such functions as the coordination and organization of symposia and workshops.

Phase I: Planning and Instrument Development

The planning process for the Max '91 program is already under way, and the results of the first efforts are reflected in this document. This planning process must continue during Phase I. The most powerful ground-based and balloon-borne instruments involve a two or three year development effort under practical funding and manpower levels. Consequently, for the Max '91 program to realize its full scientific potential, the following activities must be vigorously pursued:

- NASA and NSF need to begin a significant budgetary commitment to instrument development in FY '88 and FY '89.
- National and international communication and coordination mechanisms for both continuous (synoptic) observations and specific campaigns must be put into place and tested.
- Theoretical work must be under way from the outset in order to guarantee the stimulating interplay that is so essential to first-rate research.

Phase II: Coordinated Observations and Specialized Campaigns

We propose that the Max '91 program of coordinated observations be the period of four years, starting at the beginning of 1991. Well in advance of this time, observers must be hired and trained, the synoptic data must be flowing routinely, and observing procedures must be laid out and exchanged between all participating scientists. The campaigns must be organized around specific scentific goals, weather patterns, and observing opportunities (e.g., balloon flights and spacecraft launches). By the start of Phase II, all communication and coordination mechanisms and procedures must be in full operation, and proven in practice. The first analysis workshops, for preliminary scientific evaluation of the data sets, must be organized early in Phase II in order that the processes of data refinement and conceptual retrenchment can begin.

Phase III: Analysis and Interpretation

During the period of analysis and interpretation, which our

experience shows will require another three or four years after the end of the four-year observing period, the paradigms of the last solar cycle will be replaced by new understanding based on the observational discoveries and theoretical insights of the new cycle. It will be time for retrospective analyses, careful reexamination of the data, comparison of theory and models, and intense scientific debate. It will be too late to obtain new data, and the solar physics community can dedicate itself fully to the task of analyzing the data at hand. Both topical workshops and general symposia, similar to the coordinated data analysis workshops and the SMM workshops held at Goddard Space Flight Center and the international COSPAR and IAU meetings of the Solar Maximum Year and the Solar Maximum Analysis programs, will need to be organized around the major scientific issues identified in this report and the new insights brought by anticipated and unanticipated results.

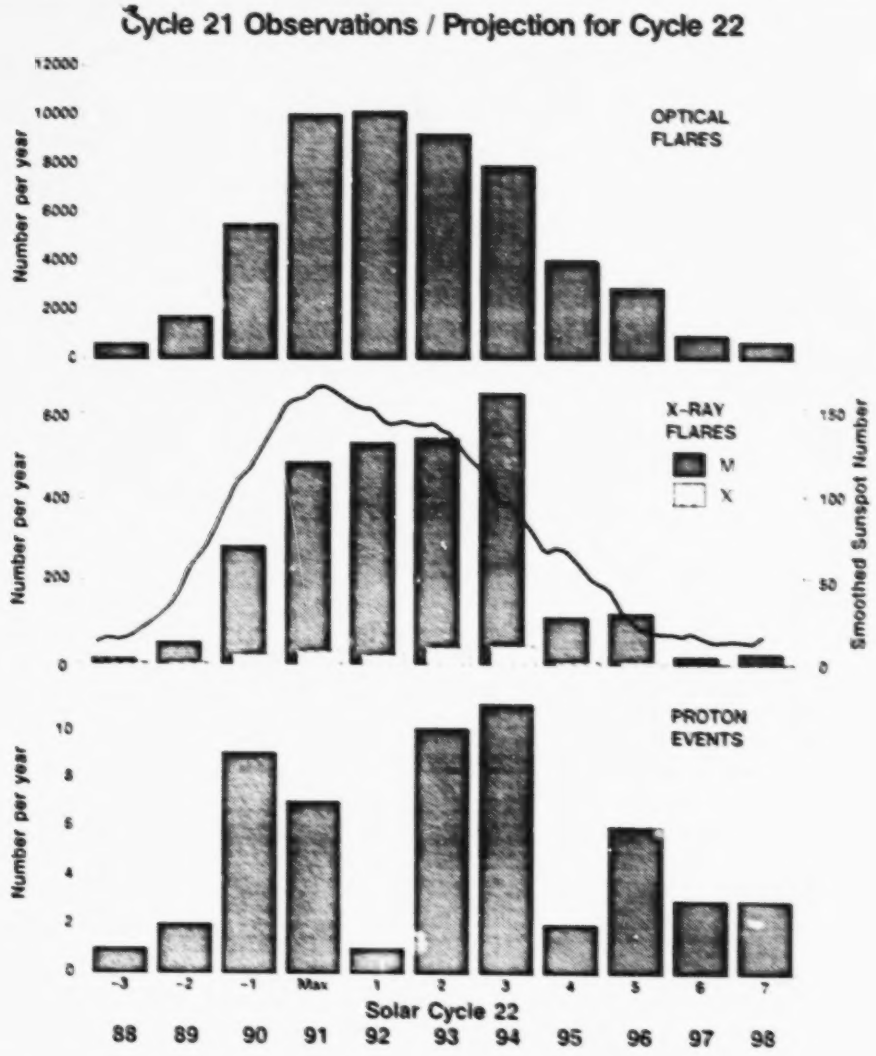


Figure 6. Histograms showing the numbers of optical, X-ray, and proton flares observed per year during the previous solar cycle, Cycle 21. The smoothed sunspot number curve for Cycle 21 is plotted over the X-ray histogram. The horizontal axis is labelled with the number of years before and after the year of sunspot maximum, which occurred in December, 1979 in Cycle 21 and which we are assuming will occur in 1991 for Cycle 22. Note that all plots show a skewed distribution with more events occurring in the years after the sunspot maximum than before. (Figure courtesy of the Space Environment Services Center, NOAA.)

CONCEPTUAL BUDGETS

These conceptual budgets for NASA and NSF are increments to already existing funding. The amounts are given in thousands of FY '87 dollars.

NASA Augmentation Budget

The balloon payloads include a strawman grouping of four instruments as discussed in this report, i.e., a hard X-ray and gamma-ray imager, a hard X-ray and gamma-ray high-resolution spectrometer, a hard X-ray polarimeter, and an optical imaging spectrometer and polarimeter. The estimates include the cost of a pointing system for the two imaging instruments. The cost estimates of the balloons and the launch campaigns are based on the assumption of two flights per instrument in 1991, 1992, and 1993, with one test flight for each instrument in 1990. We have assumed a cost of $70 K for each balloon plus $70 K per balloon for logistic support.

Balloon Program

FY	'88	'89	'90	'91	'92	'93	Total
Balloon Payloads	3,500	6,400	4,300	1,900	1,200	900	18,200
Balloons and Launch Campaigns	0	0	300	600	600	600	2,100
Total	3,500	6,400	4,600	2,500	1,800	1,500	20,300

Rocket Program

FY	'88	'89	'90	'91	'92	'93	Total
Rocket Payloads	500	1,500	1,500	1,000	500	500	5,500
Rockets and Operations	0	0	1,000	3,500	3,500	3,500	11,500
Total	500	1,500	2,500	4,500	4,000	4,000	17,000

NSF Augmentation Budget

Ground-Based Optical Observations

FY	'88	'89	'90	'91	'92	'93	Total
Planning	70	80	45	0	0	0	195
Instrument Development (1)	300	700	800	450	0	0	2,250
Testing	0	0	75	150	0	0	225
Observations/ Operations (2)	0	0	150	300	300	300	1,050
Analysis (3)	0	0	150	300	300	300	1,050
Theory (3)	100	200	250	300	300	300	1,450
Total	470	980	1,470	1,500	900	900	6,220

Notes:

(1) The principal instruments to be developed are the following:

- Vector magnetograph.
- Longitudinal magnetograph.
- Imaging spectrograph.

(2) This includes observations and operations at three observatories each with two observers funded by NSF.

(3) This includes one scientist and one new graduate student at each of three universities.

Ground-Based Radio Observations

FY	'88	'89	'90	'91	'92	'93	Total
Planning	40	30	20	20	10	0	120
Instrument Development	120	495	505	120	40	0	1,280
Testing	40	80	170	0	0	0	290
Observations/ Operations	0	60	200	345	345	345	1,295
Analysis	0	60	120	300	300	300	1,080
Theory	50	100	100	100	100	100	550
Total	250	825	1,115	885	795	745	4,615

The principal instrument developments are the following:

- Add 6 small dishes to the Owens Valley Radio Observatory (OVRO) to form a microwave imaging spectrograph.
- Install solar calibrations in additional receivers at the VLA.
- Install a digital meter/decimeter spectrograph at a location still to be determined.
- Upgrade the dynamic range of the Clark Lake Radio Observatory (CLRO).

Coordination of Observations and the International MAX '91 Program

FY	'88	'89	'90	'91	'92	'93	Total
Coordination (1)	100	100	150	150	150	150	600
International (2)	0	50	50	50	100	100	350
Total	100	150	200	200	250	250	950

Notes:

(1) One scientist plus national and international communications.
(2) Support for a mix of general meetings and topical workshops.

Total NSF Augmentation Budget

FY	'88	'89	'90	'91	'92	'93	Total
Total	820	1,955	2,785	2,585	1,945	1,895	11,785

It is assumed that the majority of this funding will come through NSF grants in the Solar-Terrestrial Program of the Atmospheric Sciences Division and the Stars and Stellar Evolution Program of the Astronomy Division.

APPENDICES

APPENDIX A. SPACE-BASED OBSERVATIONS

Solar-A

The Solar-A satellite, a project of the Institute of Space and Astronautical Science (ISAS, Japan), will carry instruments for the study of high-energy radiations from solar flares. A successor to the last maximum's Hinotori, it will be launched in August, 1991; it is an observatory-type satellite with the instruments shown in the following table sharing the ~115 kg payload.

The imaging instruments will have (almost) whole-Sun fields of view, so that no flares on the visible hemisphere should be missed. In most cases, the observations will be more powerful than the comparable observations from Hinotori and SMM.

The Solar-A Instruments

Instrument	Image Resolution	Energy Range	Source
Hard X-ray Imager	≤7 arc sec (FWHM)	20 - 80 keV	Japan
Soft X-ray Imager	~2.6 arc sec (pixels)	0.1 - 4 keV	US, Japan
Continuum Spectrometer	whole Sun	3 keV - 20 MeV neutrons	Japan
Bragg Crystal Spectrometer	whole Sun	Fe XXV, Fe XXVI, Ca XIX, SXV	UK, US Japan

Gamma-Ray Observatory (GRO)

The planned launch of GRO in early 1990 will usher in a new era of gamma-ray astronomy. Its four instruments span the energy range from 15 keV to 20 GeV and provide sensitivities about an order of magnitude better than what has been achieved to date. Although its primary objective is detection of celestial radiation, its solar capabilities are impressive. Its launch will occur on the rise of the next solar cycle, providing the potential for significant discoveries relating to the temporal and spectral characteristics of flares. Many of the solar detecting modes provide nearly continuous coverage during satellite day. We summarize these capabilities in the following table.

Capabilities of the Gamma-Ray Observatory

Energy Range	Area cm^2	Resolution		FOV	Instrument
		Time, s (range)	Spectral, % (best)		
40 keV - 600 keV	>2,000	10^{-6} - 20	30 at 88 keV	4π	BATSE
15 keV - 10 MeV	>127	0.06 - 48	7 at 662 keV	4π	BATSE
50 keV - 200 MeV	2,685	0.004 - 4	8 at 662 keV	small	OSSE
100 keV - 5 MeV	1,840	0.004 - 64	11 at 662 keV	large	OSSE shield
300 keV - 10 MeV	613	0.1 - 2	9 at 662 keV	2π	COMPTEL
600 keV - 30 MeV (effective)	100	<.01	11	80°	COMPTEL
600 keV - 20 GeV	5,800	0.1 - 66	10 at 2.2 MeV	2π	EGRET
Neutrons 20 MeV - 500 MeV					COMPTEL and OSSE

Note that BATSE will provide a flare alert for the other instruments so that they can be automatically switched into any special flare mode. Also OSSE can be pointed to Sun center to better than 1 arcminute.

Global Geospace Science

The Global Geospace Science (GGS) program, currently slated for a new start in the President's FY '88 budget, consists of four spacecraft designed to provide multipoint measurements for a comprehensive understanding of the coupling and flow of energy from the Sun through the Earth's space environment. The WIND spacecraft, which spends almost all of its time in the interplanetary medium upstream from the Earth, carries a comprehensive set of instruments for the detection of solar flare particles from plasma energies to several hundred MeV, and includes measurements of elemental and isotopic composition. WIND also carries a solar low-frequency radio experiment to track solar type II and III radio bursts from the high corona to the interplanetary medium, and a small cosmic gamma-ray burst detector, which can also detect flare hard X-ray and gamma-ray bursts with good spectral resolution. In addition, a second GGS spacecraft, GEOTAIL, designed and built by Japan, carries energetic particle detectors similar to those on the WIND spacecraft. Both WIND and GEOTAIL are currently planned for an early 1992 launch.

Ulysses

Ulysses, the spacecraft that is expected to fly over the Sun's south pole during the next maximum, will literally provide a completely new perspective on solar activity. It will carry various instruments designed to measure the in situ magnetic field, solar wind, and energetic particles over a wide energy range. Like WIND, it will carry radio antennas to measure plasma waves and to provide remote sensing of travelling solar radio bursts. Two solid-state detectors and two CsI scintillation crystals will provide spectral measurements of solar flare X-rays between 5 and 150 keV with high time resolution (up to 8 ms).

GOES

The GOES meteorological spacecraft carry some solar instrumentation; a new departure in these plans will see the implementation of the Solar X-Ray Imager (SXI) instruments. These are operational soft X-ray telescopes planned for observations beginning in the early 1990's. Data will be in the form of low-resolution, full-disk images in two X-ray passbands (10 - 20 Å and 20 - 60 Å), plus one EUV passband (255 - 300 Å). Pixel size will be 5 arcseconds. Data will be available (at rates up to one image per minute) at NOAA and USAF forecast centers in real time on a continuous basis.

In addition to their operational duties at geostationary orbit, the SXI can contribute information for retrospective science analyses in support of research missions, and as fiducial data for research telescopes. These data may mitigate limited fields of view, day/night outages, or observing program conflicts. Active experimentation might be initiated by researchers when favorable conditions are indicated by SXI. Particularly noteworthy are the SXI capabilities for long-term monitoring of X-ray flares, low-corona (magnetic) structure/evolution/rotation, X-ray coronal holes, launches of coronal mass ejections, X-ray bright points, and EUV energy input to the atmosphere at satellite altitudes.

APPENDIX B. OTHER POSSIBLE SPACE OBSERVATIONS

The Solar Maximum Mission

There is a good possibility that SMM will still be in orbit with many of its instruments still functioning during the next solar maximum. Current predictions show that in the 2σ worst case, the spacecraft could reenter the atmosphere as early as 1991. However, that time is very dependent on solar activity, and more realistic predictions indicate that SMM could well survive into 1992 or beyond. The instruments, their major parameters, and their predicted status in 1991 are listed in the following table:

Table B-1

Spectrometer		Spectral Range	Operational %
Gamma-Ray	GRS	300 keV - 10 MeV	100
Hard X-Ray Burst	HXRBS	25 keV - 500 keV	100
Hard X-Ray Imaging	HXIS	3.5 keV - 30 keV	0
Bent Crystal	BCS	X-ray emission lines	75
Flat Crystal	FCS	X-ray emission lines	≥50
Ultraviolet Polarimeter	UVSP	Ultraviolet	25
Coronagraph/Polarimeter	C/P	White light	100
Active-Cavity Radiometer Irradiance Monitor	ACRIM	Bolometric	100

Satelite de Aplicaciones Cientificas

The Argentinians are also planning a solar satellite to be called Satelite de Aplicaciones Cientificas - 1 (SAC-1) with the main objective of observing "high-energy electromagnetic and corpuscular radiation emitted in solar flares during the next maximum in solar activity." The initial plan calls for a spin-stabilized spacecraft weighing 153 kg including ~30 kg of scientific payload to be launched by NASA on a Scout rocket into a polar heliosynchronous orbit. The spin axis will be maintained pointed at the Sun to within 5° using a magnetic attitude control system and the spin rate will be 15 rpm. The scientific instruments have not been selected as yet, but the plan is that they will be built jointly by U.S. and Argentine teams.

SAMEX

A solar research satellite (SAMEX) with instrumentation capable of extensive diagnostic anlaysis of the solar atmosphere and activity processes is now under study by the DoD. The instrumentation includes a vector magnetograph/tachograph, Hα imager, and a normal-incidence XUV imager (observing in several lines in the 100 - 300 Å region), all with 0.5 arc-second resolution and with precision coregistration. SAMEX emphasizes observations of magnetic fields and field-plasma interactions over a wide range of heights and temperatures in the solar atmosphere. As support for flare studies, this instrumentation appears to form an almost ideal complement to the high-energy observations already committed to elsewhere (e.g., Solar-A).

Shuttle/Spacelab/Space Station

Little can be said about the NASA manned space program as a source of opportunities for solar observations. In the past, however, programs such as Skylab and Spacelab have made enormous scientific contributions. There are several Spacelab optical and UV instruments which could make crucially important observations from the Shuttle or Space Station if flight opportunities were available. These platforms also could support new instrumentation, even large-scale instruments developed as a part of the Advanced Solar Observatory. The essential problem in scheduling any of these instruments for Max '91 is the severely reduced number of launch opportunities following the Challenger accident.

Spartans

The Spartan program was begun as a means of deploying rocket-class scientific payloads from the Space Shuttle. Such flights offer many hours of observing, rather than the few minutes available from a rocket, and may therefore be extremely productive. However, the limited manifest of the shuttle in the early 1990's will severely restrict the number of Spartans that can be flown and it is anticipated that only rocket flights will be possible during the Max '91 program.

In the future, the Spartan capability may be substantially upgraded, for example, with longer flights made possible by servicing from the Space Station.

Solar Spartan payloads currently under development include a coronagraph system providing off-limb observations in Lyman-alpha and in visible light (Center for Astrophysics and HAO); an EUV spectrograph designed for coronal wind measurements (University of Colorado); and an instrument cluster designed for coronal plasma studies (Lockheed). The cluster includes high-resolution UV and soft X-ray imaging systems and two soft X-ray spectrographs. The EUV spectrograph and the Lockheed instrument cluster packages should be very productive in the study of active regions, and will have a good chance to observe small to medium flares if flown during the period of maximum activity.

APPENDIX C. POSSIBLE BALLOON-BORNE INSTRUMENTATION

In this appendix, we outline the scientific objectives and give brief descriptions of four instruments that have been proposed for long-duration balloon flights. These descriptions are presented as examples of instrumentation that could make the type of observations discussed in the body of this report.

Gamma-Ray Imaging Device — GRID

The primary objectives of GRID for solar flare observations are as follows:

- Identification of sites of particle acceleration and interaction.
- Study of temporal and spatial development of both the thermal and nonthermal electron components of solar flares.
- Imaging of the accelerated nucleon component of strong solar flares.

To date, solar hard X-ray images have been limited to a resolution of 8 arcseconds and to energies below 50 keV. GRID will have 5 times better angular resolution, the capability of imaging solar flares to energies as high as 1 MeV, and a factor of 1,000 improvement in sensitivity over HXIS on SMM.

The high sensitivity will, for the first time, allow studies of flares to be made on arcsecond size scales and subsecond time scales. Such scales are comparable to those associated with the magnetic structures and with the processes that modify the electron spectrum. The high sensitivity and full Sun coverage of GRID will allow the spatial study of many flares per flight, thus providing a large sample of high-energy flares for statistical analysis.

The design of GRID is based on a technique in which many spatial Fourier components of the image are measured; the image is reconstructed from these measurements by Fourier transformation in exact mathematical analogy to the technique used at any multibaseline interferometer such as the VLA. The major advantage of this technique for hard X-ray and γ-ray imaging is that arcsecond resolution can be obtained with detectors having only modest spatial resolution. This is particularly important because ~ 1 cm is the best spatial resolution that can easily be achieved at hard X-ray and γ-ray energies.

In this technique, specific Fourier components of the source distribution are isolated with individual subcollimators, each one of which consists of two widely spaced, fine-scale grids made of some high-Z material such as tungsten. Each subcollimator creates a large-scale modulation pattern of the high-energy photons from the source. Only the phase and amplitude of this pattern need be measured rather than its detailed shape, since they can be related to the phase and amplitude of a specific Fourier component. Consequently, the required detector spatial resolution is quite modest. Multiple grid pairs with a variety of slit spacings and angular orientations are used to provide numerous Fourier components carefully selected to optimize the reconstructed image.

The basic GRID design uses 32 grid pairs to measure 32 separate Fourier components corresponding to angular size scales in the range of 1.7 arcseconds to 3 arcminutes. Each grid pair subcollimator has a detector module consisting of 5 NaI(T1) rods that cover the energy range from 20 keV to 1 MeV and provide the spatial resolution necessary to define the large-scale modulation pattern. In order to image a source anywhere on the Sun, it is required that GRID be pointed to Sun center to within a few arcminutes with a stability of 0.2 arcseconds per 10 ms. Aspect information accurate to better than 1 arcsecond is provided by a pair of Solar Disc Sextants mounted directly on the grid planes.

High-Resolution Gamma-Ray and Neutron Spectrometer — HIGRANS

The primary objective of HIGRANS is to study the acceleration of electrons and ions in solar flares, through high-resolution spectroscopy of flare hard X-ray and gamma-ray continuum and gamma-ray line emission. The high-resolution measurements of HIGRANS will provide a qualitatively new window on these processes, since essentially all the nuclear gamma-ray lines and many of the important hard X-ray continuum features are unresolved by present spacecraft detectors.

Nuclear line spectroscopy, including determination of line shapes and asymmetries, will provide detailed information on the shape of the energy spectrum and angular distribution of the accelerated cone. High-resolution measurements of the flare hard X-ray continuum are equally important, since they can provide the detailed shape of the energy spectrum of the accelerated electrons, which very likely carry a large fraction of the total flare energy. High resolution is required to resolve the steep spectrum of the emission from the high-temperature "superhot" plasmas in the flare and to identify and resolve sharp breaks in the accelerated electron spectrum. These features are critical clues to the acceleration mechanism.

With the high sensitivity of HIGRANS, the temporal evolution of the accelerated ions and electrons can be closely followed. Measurements of photons and neutrons up to $\gtrsim 0.1 - 1$ GeV indicate the highest energy particles accelerated and also permit the study of high energy pion and neutron production. The very high sensitivity of HIGRANS will also allow us to see whether even small flares can accelerate ions to >10 MeV energy, and what role electron acceleration plays in very small transient energy releases, i.e., microflares.

In addition, the gamma-ray line measurements provide a new method of obtaining solar elemental abundances. The shape and temporal evolution of the positron annihilation line at 511 keV will give information on the temperature and density of the annihilation region. The characteristics of the hottest thermal plasmas created in the flare can be accurately determined from the high-resolution hard X-ray continuum measurements.

HIGRANS measurements, together with interplanetary measurements of escaping electrons and ions and ion composition, will be valuable in the study of energetic particle trapping, escape, and acceleration high in the corona.

HIGRANS is designed for high-resolution spectroscopy of gamma-ray lines from ~0.3 to 20 MeV and of hard X-ray and gamma-ray continuum from ~10 keV to ≳20 MeV. It will also make moderate-resolution gamma-ray continuum measurements from 20 MeV to ≳200 MeV and neutron measurements from ~20 MeV to 1 GeV.

HIGRANS provides spectral resolution a factor of about 50 higher than previous NaI(T1) gamma-ray spectrometers, sufficient for accurate measurement of all parameters of the expected gamma-ray lines with the exception of the neutron capture deuterium line, which has an expected FWHM of about 0.1 keV. The instrument is optimized for spectroscopy of solar gamma-ray bursts, which typically have durations of 10 to 1,000 s. The sensitivity of HIGRANS for measurements of narrow gamma-ray lines, hard X-ray and gamma-ray continuum emission, and flare neutrons is a factor of 5 to >10 higher than that of SMM instrumentation.

The instrument consists of an array of high-purity, n-type coaxial germanium detectors (HPGe) cooled to 90 K and surrounded by bismuth germanate (BGO) and plastic scintillator anticoincidence shields. Electrical segmentation of the HPGe detector into a thin front segment and a thick rear segment, together with pulse-shape discrimination, provides optimal dynamic range and signal to background characteristics for flare measurements over the energy range from 10 keV to 20 MeV. Neutrons and >20 MeV gamma rays are detected and identified with the combination of the HPGe detectors and the rear BGO shields.

High Energy X-Ray Polarimeter — HXP

The primary objectives of HXP are—

- To determine the extent of electron beaming in individual flares.
- To distinguish between thermal and nonthermal electron distributions in flares.

HXP is designed to measure the X-ray polarization of solar flares at energies between 20 and 100 keV. This energy range and the sensitivity of the proposed polarimeter are sufficient to ensure that, for the first time, truly nonthermal hard X-rays can be effectively studied. The question of interest here is whether or not the electrons that produce the X-rays are beamed during the acceleration process, i.e., whether or not the acceleration process results in an anisotropic velocity distribution. If the electrons are beamed, then the resulting X-ray emission is expected to be highly polarized; if the electron velocity distribution is isotropic, then very little polarization is expected.

It is important to note that, while the recent detection of gamma-ray beaming from flares indicates non-isotropic electron distributions, such information is purely statistical in nature. Polarimetric data, on the other hand, would provide electron beaming information on each individual flare without recourse to data from other flares.

Previous solar flare X-ray polarization measurements have failed to find evidence for polarization at the few percent level but have been limited to energies below ~20 keV, where thermal emission is known to dominate. A factor of three improvement in sensitivity is required to detect and reliably measure the polarization predicted by current theoretical models. HXP achieves this sensitivity and can be flown on a balloon so that shuttle or other space flights are not required. (They are, of course, still desired since they may lead to longer observing time.) The new instrument operates at higher energies than previous experiments, thus avoiding the detection of pure thermally produced X-rays, which are expected to be polarized at a very low level by back scattering in the dense solar atmosphere.

The most sensitive X-ray polarimter previously flown was the STS-3 instrument flown on the space shuttle in March 1982 by the Columbia X-ray group. The instrument exploited the polarization dependence of Thomson scattering. The scattering targets were 12 rectangular blocks of metallic lithium, monitored on two of the four sides by xenon-filled proportional counters; there were thus effectively six targets. The low-energy threshold was set at ~5 keV by photoelectric losses in the lithium, with the high-energy cutoff set by the transparency of the xenon proportional counters at ~20 keV.

The HXP instrument overcomes many of the limitations of the STS-3 instrument. This new instrument still exploits Thomson scattering, but instead of using a large number of small scattering blocks, it has a thin, large-diameter (60 cm) beryllium scattering plate. By making the target a thin plate with a thickness equal to about one-third of the scattering mean free path, there is a high probability that a scattered photon will exit from the plate without undergoing multiple scattering and degrading the polarization response. The scattering plate is made by beryllium to avoid the chemical contamination effects that were encountered with the lithium scattering blocks in the STS-3 polarimeter. This design achieves a high sensitivity with only a few simple components. It is estimated that the weight of the instrument and gondola is ~1,500 pounds, well within the capabilities of standard balloons used for long-duration flights.

A further improvement in the polarimeter over STS-3 is the use of NaI(T1) detectors instead of xenon gas counters for

sensing the scattered radiation. Such detectors can easily be designed to have high efficiency at energies up to 100 keV or more.

If polarized X-rays are incident on the scattering plate, the signals recorded by the various NaI(T1) detectors will be different. The two Stokes parameters defining the linear polarization of the incident radiation can be determined from the ratios of the counting rates in the different detectors. In this design the results are sensitive to the relative efficiencies of the various detectors, which, in turn, depend on the X-ray spectrum of the flare. While every effort will be made to use detectors of equal sensitivity and to monitor their relative sensitivities with radioactive sources, it is clear that at some level, instrumental polarization effects will arise from residual differences in the detectors.

The difficulty will be overcome by rotating the polarimeter about the line of sight to the Sun at 6 rpm. Any polarization of the solar X-ray flux will then result in a modulation of the signal in each detector with a frequency equal to twice the rotation frequency. The amplitude of the modulation provides a measure of the degree of polarization, while the phase angle is directly related to the position angle of the polarization vectors. In this way, the effects of detector differences can be eliminated and sensitive measures of the polarization can be made with a time resolution of 5 s.

The sensitivity of HXP depends on the hard X-ray intensity and the spectral shape. It is estimated that the minimum detectable polarization at the 3σ level for an M2 class flare in 10 s of observing time is 2% in three energy bands between 20 keV and 60 keV and 5% in two bands between 60 keV and 100 keV. This is assuming that the X-ray spectrum is a power-law with a photon index of 3.0 and that the instrument is at an altitude of 130,000 ft with the Sun directly overhead. For an X2 class flare with the same assumptions, the corresponding sensitivities are one-third of these values, or the same values in 1 s instead of the 10 s observing time. We expect higher polarization at high energies where thermal emission is less pronounced. These sensitivities are more than adequate to provide critical tests of existing solar flare theories. Clearly, HXP is well suited to answering the outstanding questions regarding electron transport and thermalization in solar flares.

Solar Optical Universal Polarimeter — SOUP

The primary objectives of SOUP are as follows:

- To measure vector magnetic and velocity fields in the solar atmosphere with much better spatial resolution and for much longer time intervals than can be achieved from the ground.
- To measure the buildup and release of magnetic energy in active regions over periods of several days.
- To study the magnetic field changes associated with transient events such as Ellerman bombs, flares, and flux emergence.
- To detect and classify wave modes on fine spatial scales in the photosphere and chromosphere.

SOUP is designed to study intensity, magnetic, and velocity fields in the photosphere and low chromosphere. Observations at balloon altitudes would enable these measurements to be made free of atmospheric disturbances. A spatial resolution of 0.5 arcsecond could be achieved, compared with ~2 arcseconds on the ground and a stability of 0.01 arcsecond would be possible, some 30 times better than on the ground. The instrument includes the following components:

- A 30-cm Cassegrain telescope.
- An active mirror for image stabilization.
- White light film and TV cameras.
- A birefringent filter, tunable over 5100-6600 Å with a 0.05 Å bandpass.
- A 35-mm film camera and a digital CID camera behind the filter.
- A high-speed digital image processor.

The field-of-view of the telescope is approximately 4 arcminutes in diameter, and each camera can be adjusted in magnification up to this limit. The tunable filter has prefilters for selecting any of eight spectral regions, 5 to 8 Å wide. The lines available include Hα, He D3, Na D2, Mg b, and several Fe I lines for magnetic and Doppler measurements. A polarization analyzer allows precise measurement of circular and linear polarization for making longitudinal and transverse magnetograms in the photosphere and temperature minimum region. In addition, images spaced at intervals across the Hα line profile show the paths of chromospheric fibrils much better than single frames, allowing the connectivity of magnetic field lines to be inferred. The white light frames can be used to measure transverse velocities from proper motion of the granulation pattern. Thus, the flow patterns which shear the magnetic fields of an active region can be measured independently of the fields themselves.

SOUP flew on the shuttle Spacelab 2 mission in August, 1985, and one day of observing time was available for SOUP during the flight. Over 6,000 frames of diffraction-limited white light data were collected, and these have led to new discoveries on granulation, large-scale convection, waves, and sunspot dynamics. A second shuttle flight on the Sunlab mission was planned for 1988, but this has been effectively cancelled by the Challenger accident. High-resolution imaging on balloon flights was achieved by Project Stratoscope in the late 1950's, and has been exploited since then by German, Russian, and Japanese groups for additional white light studies. Balloon flights of SOUP would produce our first views of active region magnetic fields at a resolution approaching the size of the basic flux tubes themselves.

APPENDIX D. CURRENT LONG-DURATION BALLOON FLIGHT CAPABILITIES

Long-duration balloon flights (LDBF's) can provide 15 to 20 days at float altitude by circumnavigating the globe. Up to ~3,000 lbs total payload weight can be carried by the present standard 28.4 million cubic ft zero-pressure balloons to altitudes of ≳ 130,000 ft (40 km). For standard zero-pressure balloons operated in the RAdiation COntrolled balloON (RACOON) mode, the temperature of the gas, and therefore the balloon altitude, is controlled essentially by the radiation received from the Sun and the Earth. If the balloon initially reaches a high daytime float altitude, it will remain above the tropopause in its day-night excursions under normal conditions without ballast drops. With a small ballast drop each day to compensate for gas loss, the initial daytime float altitude can be maintained for weeks. The strong stable zonal winds of the summer season at mid-latitudes can bring a high altitude balloon around the world in 12-20 days. The main characteristics of RACOON LDBF's are—

- The balloon is at high altitude during sunlight hours but drops during nighttime, making RACOON flights particularly suitable for solar observations.

- Essentially, ~12 hours of continuous high-altitude observations are obtained each day, as compared with typical low-altitude Earth-orbiting spacecraft (such as SMM), which have an ~95-minute orbit with ~40 minutes Earth shadow each orbit. For SMM, the start or decay phase of a large flare can be missed. Coverage through an entire flare, including at least 10 minutes after the impulsive phase, is important to observe the delayed emissions including neutrons, positron-annihilation radiation at 0.5 MeV, and the effects of delayed acceleration. It may be possible to obtain ~24-hour coverage at gamma-ray energies with flights over Antarctica during its summer.

- The background for hard X-ray and gamma-ray measurements at balloon altitudes is particularly low and very stable, unlike the background for low-altitude spacecraft, which changes drastically through the orbit. Thus, the effective sensitivity is significantly greater and data analysis is far simpler. Since the energetic particle radiation environment is much less severe at balloon altitudes than for low-orbiting spacecraft, activation of the detector and radiation damage to the electronics are negligible.

- It is simple and cheap to provide cryogenic cooling for balloon-borne instrumentation, but extremely expensive and complex solid-cryogen or mechanical coolers are required for spacecraft because of the weightless environment in orbit.

- Because of the much more benign launch environment and the capability for repairs after each flight, balloon experiments need not be designed to space-qualified specifications. These are major cost drivers for space experiments.

At present, around-the-world flights are possible only in the southern hemisphere, for political reasons. Since the winds are favorable only in the local summer, a season of ~3 months (December to February) is available. Trans-Pacific flights from the U.S. to China, however, can offer 5-10 day durations in the northern hemisphere summer, as well as opportunities for collaborations with the People's Republic of China (and Japan). Chinese scientists have expressed strong interest in such collaborations.

In 1983, a 15-million-cubic-ft balloon with an ~1,200-lb payload (from Case Western Reserve University) designed to search for solar flare neutrons was launched from Alice Springs, Australia, and made a circumnavigation of the globe in the southern hemisphere in ~18 days. The ground command cutdown of the payload from the balloon malfunctioned, however, and the balloon continued past Australia after 22 days until the automatic cutdown was triggered and the payload was parachuted into the Indian Ocean.

In 1987, two exploratory RACOON balloon flights were launched from Alice Springs, Australia. One of them (from the University of California, Berkeley) carried a complement of hard X-ray and gamma-ray detectors, including both liquid-nitrogen cooled germanium detectors for high spectral resolution and large-area phoswich scintillation detectors for high sensitivity, for observations of microflares and flares from the Sun. The other payload (from Louisiana State University) was a passive stack of emulsions for cosmic ray studies. These payloads were carried by the standard, 28.4 million cubic ft, 0.8 mil polyethylene, zero-pressure balloons developed for normal short-duration flights. The resources available for the UCB RACOON balloon flight: ~1,800-lb payload capability and 900 lb of ballast, ~100 watts from solar cells, and ~60 bps data rate over ~65% of the globe through GOES geosynchronous satellite telemetry links, and tracking to ~10 km via ARGOS, are sufficient for many studies of solar activity.

The LSU payload was launched on January 25, 1987. Approximately 1,500 lb of ballast was dropped at the rate of ~250 lb per night to keep the balloon at high altitude at night. After six days, the balloon encountered unusually cold cloud cover over South America and came down in Paraguay, where the payload was later recovered.

The UCB balloon payload was launched on February 9, 1987. Because of a malfunction, all the ballast was dropped at launch, and the balloon's float altitude slowly decreased due to gas loss. After twelve days, the payload was cut down by

PRECEDING PAGE BLANK NOT FILMED

command and was recovered in Brazil. With an operational auto-ballast system, this balloon would very likely have completed its circumglobal flight in ~18 days.

Improvements to LDBF Capabilities

The reliability of LDBF's needs to be improved and the resources available (weight, power, telemetry rate, command capability) should be expanded in the next few years prior to the next solar maximum. The main areas which need work are as follows:

- Auto-ballast system

  For solar observations, the main requirement is a highly reliable and efficient ballast system which will keep the balloon above the tropopause when the balloon is over very cold cloud cover at night, and keep the daytime altitude above ~120,000 ft so that high quality, low energy (~15 - 50 keV) measurements can be obtained.

- Command system

  A simple system to get commands to the balloon as it goes around the world is needed. This could be accomplished through the present command capability of the GOES network.

- Telemetry system

  Expansion of the current GOES telemetry link to include the Japanese HIMAWARI spacecraft would be especially useful for checkout at Alice Springs. A telemetry link with a high data rate capability would be highly desirable, although currently developed balloon data storage systems are capable of storing >10 gigabits with input rates up to ~1.4 megabits s^{-1}. Telemetry of ~1 - 10 kbps through TDRSS appears possible.

- Navigation

  An OMEGA/TRANSIT navigation system for obtaining on-board the position of the balloon is currently under development and appears ready for flight tests.

- Power

  Solar cell/battery systems can be improved and expanded with better cells, solar orienting, etc., to provide higher output.

As pointed out earlier, even the present balloon capabilities are adequate for many solar experiments, and the developments outlined here could be accomplished at very modest cost.